Improving dual purpose wheat cropping in Tasmania by evaluating defoliation strategies and new genotypes

By

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Abstract

Wheat cultivated for forage plus grain is commonly termed as dual-purpose (DP) crops. The climate in Tasmania fulfils the requirement of winter wheat vernalisation therefore winter types are preferred for DP cropping. To extend our understanding about wheat defoliation management and identification of potential varieties for Tasmania, three experiments were conducted at Tasmanian Institute of Agriculture, Mount Pleasant Laboratories, Launceston, Tasmania from 2015-16. Experiment 1 (Chapter 3) was conducted in a glasshouse to study the relationship between defoliation, plant morphology and crop recovery. Four wheat varieties (Tenant, Revenue, Chara and Bolac) were defoliated using Clip and Crash strategies at four different plant anatomical cut points (LL75%, LL50%, LL100% and LS50%) at mid-tillering (GS25). Clipping at 50% and 75% of leaf length had positive effects on regrowth and increased crop height by 15%. Crash treatments were cut at the end or half way along the leaf sheath and produced more forage but affected plant regrowth at the start of stem elongation (GS30). Experiment 2 (Chapter 4) was established in a field to study the effect of cutting height on forage yield and crop regrowth of three wheat varieties (Bolac, Revenue and CS170). Five cutting heights at were imposed at mid-tillering (GS25) to estimate forage yield. Treatments included Clipping (cutting at ground level, 3 and 5 cm) and Crash (cutting at 8 and 10 cm above ground level). Clipping treatments did not affect plant height or biomass compared with the uncut control whereas the Crash treatment significantly affected plant height at the start of stem elongation (GS30). Moreover, forage production at mid-tillering (GS25) was significantly influenced by cutting. The Biomass yield of Clipped plot was 50% less than control, whereas, defoliating above 5 cm resulted plant height similar to uncut. Tall and medium statured varieties produced 50% more forage yield than prostrate. Defoliation below 5 cm affected plant regrowth and biomass. The findings from both experiments above were applied in Experiment 3 (Chapter 5) to evaluate 99 genotypes including landraces and commercial from China and Australia to identify the new varieties suitable for DP production under Tasmanian conditions. Evaluation of two levels of cutting treatments (control and cut at 5 cm) at the start of stem elongation (GS30) showed differences among genotypes in calendar days, forage yield, plant height and GDD (Growing Degree Days). Genotype H-051 had the greatest height (46.6 cm), higher forage yield (2.23 t ha^{-1}) and biomass yield (3.39 t ha^{-1}). Genotypes H-061 and Mackellar showed the best potential regrowth capacity by attaining height (60 and 64 cm respectively) after cutting at GS30. The genotypes accumulating less days to reach GS45 had less height than genotypes accumulating maximum GDD to GS45. The regrowth of the genotypes after

defoliation was related to the number of leaves on main stem and tillers plant $^{-1}$. the genotypes reaching stem elongation stage late had higher forage and biomass yield. The genotypes producing higher forage yield and recovering height similar to uncut are recommended to be evaluated at other location across Tasmania for further screening.

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Table of content

List of Figures

List of Tables

Chapter 1. Introduction

Livestock is fed with crops like forages, canola and cereals. During winter in temperate and southern grassland regions of Australia due to low temperature the quantity of pasture forage in not sufficient (Dove and Kirkegaard, 2014, Grain & Graze, 2016). Cereals (wheat and barley) and canola are used as Dual Purpose (DP) crops to provide extra grazing for livestock over winter (GRDC, 2016). Early sowing of DP crops help prolongs the availability of forage and discouraging grazing after flowering enables grain to be harvested, thus benefiting the farming system by providing alternative feed source as crop forage, longer grazing window, weed control, grain yield and increases over all farm profitability (GRDC, 2016, Kirkegaard and Filmer, 2008, Moore, 2009).

Wheat is an important DP crop with the highest annual grain production of all cereals in the world (Khalil et al., 2011). DP grazing of wheat is common practice in Australia, Morocco, Argentina, Syria, Uruguay, USA and New Zealand (Harrison et al., 2011a). Varieties for dual-purpose wheat are usually selected from a grain-only production system, although the removal of above ground biomass can affect the yield potential of the grain-only variety (MacKown and Carver, 2007). Increasing grain yield is the highest breeding priority for commercial wheat varieties that are used for both DP grazing and grain production.

The life cycle of wheat begins at germination passing through several critical morphological stages, such as seedling emergence, tillering, stem elongation, booting, flowering, and maturity (González et al., 2002). In winter wheat, stem elongation begins when the crop has received sufficient vernalisation, has a long enough photoperiod and the temperatures are warm enough for growth (Chen et al., 2009). Throughout this thesis, growth stages (GSs) are referred to on Zadoks scale (Zadoks et al., 1974)

Winter wheat is important and well utilised for DP cropping due to its high feed nutritive content. It contains 79.8% crude fibre, 16.2% of N-free extractives with high dry matter digestibility, and is rich in crude protein (0.4%) and metabolized energy (Dove et al., 2002b). Wheat can give good economic returns subject to proper grazing and management practices (Aase and Siddoway, 1975).

Studies conducted in Victoria, Australia show that grazing during the stem elongation stage affected the grain yield of almost all varieties because of reduced fertile tiller and low nitrogen in stem and leaves (Hacking, 2006). Termination of defoliation at or before the start of stem elongation (GS30) minimises the losses in grain yield because after GS31 the probability of removal of the apical meristem due to grazing is high leading to a reduction in the number of viable tillers and potential yield loss (Harrison et al., 2011a). Regardless of whether the crop is irrigated or rainfed the capacity of the crop to regrow after the stem elongation stage is limited due to lost tillers (Harrison et al., 2011a).

Height of wheat is one of the main factors contributing to the total dry matter production and susceptibility to lodging (Brancourt-Hulmel et al., 2003). Studies show that prostrate/semi dwarf varieties of cereals are more sensitive to defoliation than taller varieties, as the leaf area of dwarf varieties at anthesis is more critical for grain yield than taller varieties. Therefore, defoliation should be terminated earlier in dwarf varieties compared with tall varieties (Redmon et al., 1995). On the other hand, modern semi dwarf varieties are resistant to lodging at the expense of reduction in yield in some varieties (Brancourt-Hulmel et al., 2003) though many modern varieties have higher harvest-index and comparable grain yield to tall varieties (Harrison et al., 2011a). Moreover, grazed crops are reported to be more prostrate, have more decumbent leaves, increased number of tillers and reduced plant height at maturity (Harrison et al., 2011a). Thus, grazing of tall varieties can be used as a management strategy to minimise lodging.

While there are a range of existing semi-dwarf and tall varieties of wheat currently being used in dual purpose production in Australia, wheat breeders are continuing to develop or introduce new genotypes as part of their plant breeding programs. The potential for these new genotypes to be used in dual purpose cropping should be evaluated. To achieve this aim requires a reproducible technique that is efficient and suited for screening a number of genotypes is a short period of time. Approaches based on mechanical grazing in pots in the glasshouse or in short rows in field conditions are better suited to this aim compared to grazing by livestock. Defoliation strategies like early, late, Clip (cutting few centimetres of lamina from top) and Crash (cutting plant near to ground level) have been used (Seymour et al., 2015). Whereas, cutting of wheat according to plant morphological stage (rather than GS) has been discussed less in past work.

The aim of this research is to develop a defoliation strategy to evaluate the regrowth potential of the residual biomass of different wheat varieties under glasshouse and field conditions. Defoliation experiments were preferred over grazing experiments to minimize the confounding effects of grazing by animals like trampling and patchy grazing. Wheat was defoliated either at GS25 according to the plant morphology (Chapter 3) or, defoliated according to height from ground level (Chapter 4). Cutting strategies and varietal performance were quantified in terms of plant height, forage yield and chlorophyll. Based on the findings of Chapter 3 and 4, it was concluded that a single cutting height would be applied to a range of wheat varieties (Chapter 5) from China and Australia and grown in field conditions.

Chapter 2. Literature review

2.1 Dual purpose cropping

Cereals crops may be used both for forage and grain (Redmon et al., 1995). Dual-purpose (DP) (Malinowski et al.2003) cereals like wheat, barley, oats and triticale are potential source of feed and contributes in to the agricultural economies of many countries (Kaitibie et al., 2003). Wheat provides 20% of food energy and protein worldwide (Heuze and Tran, 2015). The extent of grazing crops over winter and harvesting for hay, silage or grain depends on the ability of the crop to recover after defoliation. This approach is termed dual-purpose cropping (Malinowski et al., 2003) and is an innovative way to increase per unit area production (Dove and Kirkegaard, 2014, Grain & Graze, 2016). DP cereals can also be rich source of high-quality forage due to their protein content, energy, minerals and have low fibre, which makes them comparable to other forage crops like lucerne in terms of digestibility and crude protein (Hossain et al., 2003).

DP wheat cropping zones are in both rainfed and irrigated areas of Australia, with DP grazing mainly being conducted in temperate and southern grasslands regions (Figure 2.1). Livestock feed shortage in these areas is a common issue in winter as crop growth declines due to the cold conditions. To address the issue of winter feed gap, winter wheat is generally preferred as it can be planted earlier and has a longer vegetative phase due to its requirement for vernalisation compared with spring varieties. This contributes to its availability as forage during winter, when choice of pasture forage is limited (Dove et al., 2002b, Kelman and Dove, 2007, Harrison et al., 2011b).

In Australia, after the success of DP cereals in high rainfall zones it was also adopted in the dry zones (Moore, 2009). The increasing market for meat, dairy and wool industries motivated growers to address the feed demand of animals associated with this industry. This adoption of DP wheat production into extensive agricultural farming systems demanded appropriate crop management practices like optimum sowing dates, selection of high biomass and grain yielding varieties, knowledge of GS for grazing and grazing duration.

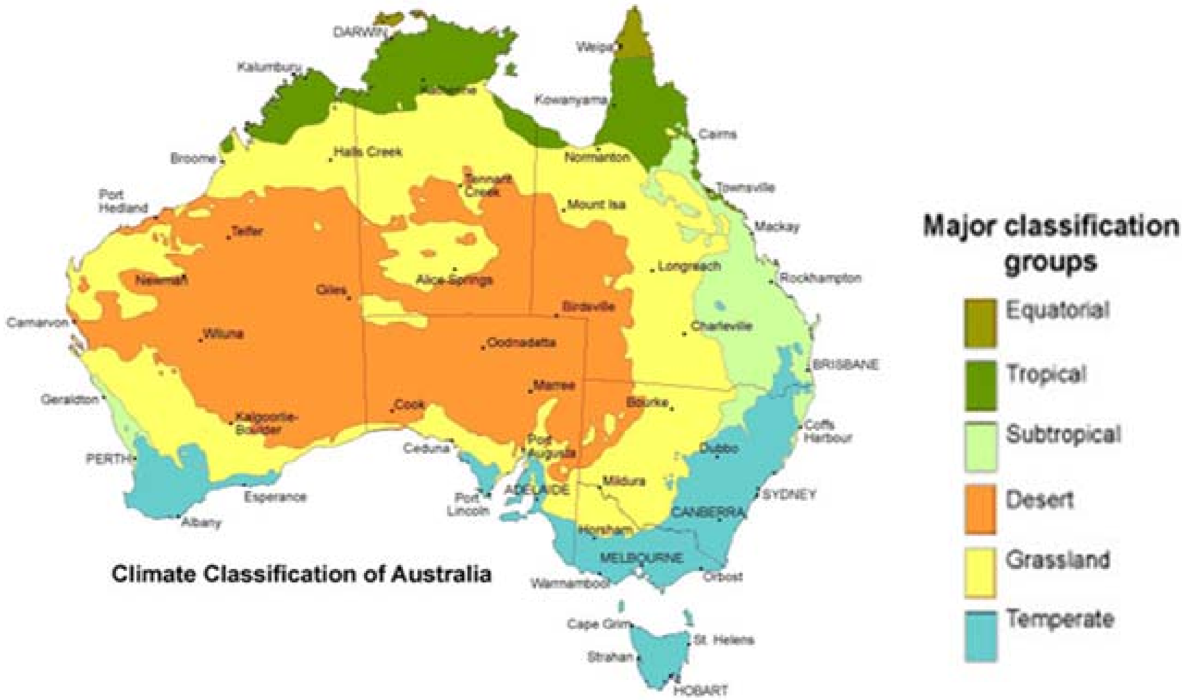


Figure 2.1. Major climatic classifications of Australia based on past 30 years climatology conducted by Australian Government, Bureau of Meteorology (Grain & Graze, 2016). Crop grazing is mainly conducted in cool temperate regions and to a lesser southern grasslands region.

Wheat as a forage is consumed by livestock either by grazing directly or indirectly by clipping mechanically. It is common practice for farmers to allow livestock to graze crops in Australia, Morocco, Argentina, Syria, Uruguay, USA and New Zealand (Rodriguez et al., 1990). Tasmania contributes a small portion (0.1%) to wheat total production in Australia, primarily because the climate favours lower value general purpose wheat varieties over higher value hard-wheat used for milling and relatively small arable land mass compared with mainland Australia (Freshlogic, 2014). Australia is among the world's leading producers of cattle and sheep, around 0.7 million cattle heads and 2.2 million sheep were recorded in Tasmania and about 60,000-80,000 tonnes wheat was produced in Tasmania with average yield of 4.4 t/ha (GRDC, 2017). The production of winter wheat in Tasmania depends on the climatic conditions over the year, farm management practices and selection of DP varieties. Improvement in crop performance needs understanding of the crop behaviour and performance in different localities and environments (Davidson et al., 1990).

2.2 Economic perspectives of dual-purpose cropping

Cereal-livestock enterprises have been developed and spread rapidly throughout the 21st century (Price and Hacker, 2009). The increase in the dairy meat and wool production and consumption meant more feed was required to raise the flocks and/or mobs. This resulted in an increase in area of cultivated area of forage crops like lucerne (*Medicago Sativa*) (Amossé et al., 2013), berseem (*Trifolium alexandrinum*), clover (*Trifolium*) and oats (*Avena sativa*) over a large area and consequently, the area under cereal cultivation for grain-only crops was gradually reduced in favour of forages. Because of this change in the cropping pattern, DP wheat provided a solution to supply animal forage as well as grain. When managed properly as a DP crop, cereals are financially profitable in terms of both fodder and grain production per land area (Arif et al., 2006, Hossain et al., 2003). Indeed, the use of DP cereals and brassicas for winter feed has the capacity to increase profit by AUD$10,000 to AUD$20,000 per farm (Kirkegaard and Filmer, 2008). The DP wheat cropping is now a well-established management practice in Australia and research has been carried out to raise the economic return and profit margin by improving the quality and quantity of the crop (GRDC, 2017).

High profit margins from grazing wheat are achievable with good management practices. In a recent industry report, early sown long-season wheat varieties had a ratio of net return increase > $250 ha^{-1} over early-sown short season varieties (GRDC, 2017). The profit margin of DP crops fluctuates due to suitability of varieties to location, sowing dates and defoliation strategy but if the crops are well managed the profit margin can potentially be high. If the value of grain is relatively higher than fodder, then planting later and grazing less in some cases can result in greater net returns (Alward and Joern, 1993).

2.3 Animal nutritional value of DP wheat

During a typical growing season, autumn forage is a priority feed option for grazing animals due to the shortage of other pasture feed at this time of the year (MacKown and Carver, 2007). Growth rates of pastures are slow during winter due to the cold temperatures. During these periods, winter wheat varieties are the best options for providing green feed to animals. Moreover, it is one of the most highly nutritious livestock feeds available at this time of the year (Dove et al., 2002b). The grain and biomass nutritional capacity for livestock is dependent on the rate of pre-and post-defoliation photosynthetic activity, which contributes to water-soluble carbohydrates (WSC) that are stored in leaves and stems during the vegetative stage (Harrison et al., 2011a). These assimilates are relocated to kernels after anthesis (Ehdaie et al., 2006).

Wheat forage can provide 12 MJ ME/kg (mega joules of metabolisable energy per kg) of dry matter (DM) and 22% crude protein (CP) (Table 2.1). In contrast, ryegrass and oats may offer as low as 9.5 - 10 MJ ME/kg DM and 17-25% CP. Forage crops like sorghum and forage legumes are also used both for grazing and conserved as feed for winter, but generally the quality of pasture, forage and hay is poor. Low quality pasture and forage limits number of factors like animal growth, delaying sexual maturity, conception and calving (Courtney and Rutherglen, 2002, Dove et al., 2002). Therefore, improving the quality of forage provided to animals helps in increasing their growth and productivity. Crops should be selected according to the nutritional value and requirement according to the animal nutritional needs (Table 2.1).

Table 2.1 Nutritive value of various forages and grain crops (DAF, 2013, Courtney and Rutherglen, 2002).

Crop	CP%	NDF %	ADF%	DMD%	ME
Wheat	22	-	-	90	12
Ryegrass, Clover	25	30	25	-	10
Lucerne hay	20	45	21	-	9.5
Fertilised tropical grass-green leaf	15	62	35	-	9
Forage sorghum	14	68	40	90	8-9.5
Cereal grain (barley, maize)	10	18	9	90	13
Oats	17	55	30	90	9.5

CP = crude protein, NDF = neutral detergent fibre, ADF = acid detergent fibre, DMD = dry matter digestibility and ME = metabolised energy (MJ/kg DM).

2.4 Benefits of DP wheat cropping

In DP wheat cropping forage and grain yield are also corelated. Both these factors can alter the conditions favouring higher production. Like, delaying grazing until after the start of stem elongation (GS30) (Zadoks et al., 1974) has been studied by several authors (Redmon et al., 1996, Khalil et al., 2011, Arzadún et al., 2006) and reduces grain yield by affecting dry matter remobilization from vegetative structures to the grain (Arduini et al., 2006). This means that defoliation (intensity and duration) contributes to the forage yield and its effects on latter reproductive phase results in delayed heading and lower grain yield (Khalil et al., 2011). Similarly, although protein content in grain may not affected by forage removal, in one study yield losses were 16% when forage removed at GS31 and 33% at GS31 (Royo et al., 1994). Alternatively, there is also evidence that defoliation has no effects on the grain protein and kernel diameter (Khalil et al., 2002).

Wheat grain and dry matter yield is at risk of damage due to frost induced sterility and abortion of formed grains at anthesis (Barlow et al., 2015). Frost kill off the anthers or developing grain, severely limiting grain yield. Grazing allows a farmer to manipulate crop development. An effective grazing management can be frost management tool (Nuttall et al., 2017). The need to regrow will delay the timing of flowering, which might push it past the critical period when the risk of frost is highest. Early sowing enables help to establish healthy crop stand allowing grazing during tillering stage. This shift the crop anthesis stage up to 36 days during this period the night temperature is 0ºC. Therefore, grazing ensures grain yield in addition to feed availability during frost period (Crimp et al., 2016).

Wheat grain yield losses depend on variables like lodging, sowing time and grazing duration. Lodging can reduce yield from 12-66% when it occurs at anthesis or early grain filling. Cutting of wheat as forage at or before stem elongation is an alternative to reduce lodging (Taylor et al., 2010). Yield losses can be minimized through grazing, to restrict height and lodging potential.

2.5 Mechanical defoliation

Mechanical defoliation or cutting of forage is used to simulate grazing in controlled conditions in both field and pot experiments, with grain yield varying with variety (Kelman and Dove, 2007, Wells, 1971). Cutting is preferred in some experiments as it eliminates any confounding effects of livestock due to trampling of plants, causing damage. On the other hand, mechanical grazing is not truly representative of how livestock preferentially graze selected parts of the plant e.g. leaves as compared with stems (McNaughton, 1979). These approaches are particularly relevant to this thesis, which aims to evaluate a range of genotypes from a breeding program for their potential as DP crops. To achieve this requires techniques that are efficient and reproducible.

Some authors have categorised mechanical cutting of forage into two groups, e.g. ‘Crash’ cutting and ‘Clipping’ (Dunphy et al., 1982, Seymour et al., 2015). In Crash cutting, plants are cut near ground level and generally at or below ligule at a height of around 0 to 5 cm. Clipping refers to defoliating few centimetres from the top of the leaf lamina in a way that most of the leaf tissue remains with plant (Seymour et al., 2015) i.e. light defoliation. Given sufficient time available for recovery, Crash defoliated crops (after full recovery) can produce more than 20% forage compared with Clipping (Seymour et al., 2015, Arzadún et al., 2006). Similarly, defoliation below a critical limit (generally Crash) may result in low growth rates and increased length of time between grazing and anthesis (Harrison et al., 2011a, Bell et al., 2015). In other studies, Crash defoliation truncated the grain filling stage and delayed the morphological development (Winter and Musick, 1991). These reports all conclude that the extent to which defoliation effects the regrowth depends on the intensity. Clipping (cutting small amount of green tissue from top to bottom) typically has less negative impact on regrowth compared with Crash cutting.

2.6 Wheat (variety) suitability for DP production

The DP productivity of wheat depends on the performance of a given variety under certain agro-climatic conditions. The selection of variety in each region depends on climate and traits like grain yield and straw (dry stalk after grain yield), the quality and quantity of what is dependent on the association of primary (agronomic and genetic) and secondary (tolerance to pest and diseases) characters that are considered during variety selection (Brancourt-Hulmel et al., 2003, Zhu and Khan, 2001, Brummer, 1999). Even though wheat varieties differ in yield and yield components (Mehasen, 1999, Metwally et al., 1998, Hassanein et al., 1997), varietal differences may be responsible for variation in grain, straw and biological yields and other yield components (Abdel-Ati and Zaki, 2006). The biomass and grain yield of defoliated and non-defoliated wheat varieties sown at different times was observed and it was found that the response of each variety to defoliation was different with regards to the GS at which plants were defoliated (Table 2.2).

Since forage yield is generally related to green leaf area, prostrate / semi dwarf varieties are usually more sensitive to defoliation than taller varieties, and so defoliation should be terminated earlier in semi dwarf varieties (Redmon et al., 1995). Tall varieties generally have greater leaf area than dwarf varieties, but not always (Araus et al., 1993). Tall varieties may lodge (semi dwarf less so), so the removal of biomass during grazing can mitigate against this risk (Redmon et al., 1995).

Tall wheat varieties are preferred in DP wheat cropping due to high forage productivity, but they are more prone to falling over as plant is too heavy or the crops do not have sufficient anchoring in the ground at maturity. Cutting reduces plant height up to 4.1% with no effects on spike length and number of nodes per tiller (Winter et al., 2016). Grazing minimizes the risk of lodging at harvest stage as biomass removal will restrict the crop from getting too tall (Redmon et al., 1995).

New varieties are routinely incorporated into Australian wheat production through plant breeding or the introduction of new genotypes from overseas that are then evaluated for adaptation to local growing conditions. The types of traits evaluated include, for example, plant height, maturity, vernatilisation response and quality. Including an evaluation of the potential of these new varieties for DP production could improve the adoption of these new varieties into Australian farming systems.

Table 2.2. Grain yield (t ha^{-1}), biomass defoliated (t ha^{-1}) and net return (\$ ha^{-1}) recorded for wheat varieties at Warialda, Australia in 2011 (GRDC, 2017).

Sowing date	Variety	Defo GS	Grain yield			Biomass Def	Net return	
			Grain only	Def	Change		Grain only	Def
22 May	Gregory	-	4.9	-	-	-	1225	-
	Sunbrook	-	5.6	-	-	--	1400	-
7 Apr	Mackellar	-	6.8	5.2	-1.6	1.40	1496	1536
	Wedgetail	31	5.0	4.5	-0.5	0.35	1250	1223
	Sunbrook	33	5.3	2.7	-1.6	1.04	1325	966
	Gregory	41	4.3	3.8	-0.5	0.35	1075	1048

Note: Defo = Defoliation and Def = Defoliated

2.7 DP wheat sowing time

Improving variety performance by optimizing the sowing date is a key factor in maximising production and has played a vital role in influencing forage plus grain production under DP systems (Arzadún et al., 2006, Amrawat et al., 2013). Wheat sown early during Autumn (March in the southern hemisphere) can extend the forage growing season to ensure maximum forage production. Autumn sowing also provides warmer temperatures for vegetative growth (Davidson et al., 1990), increasing leaf extension rates (growth ceases between 0 to 5ºC) (McMaster and Wilhelm, 1997, Gallagher et al., 1979).

Management of DP wheat sowing time (Early March) benefits in higher farm productivity due to more tolerance of grazing then latter (April and May) sown in Australia (Johnson, 2016). As the vernalisation requirement keeps the vegetative phase long prior to reproductive growth, therefore the winter wheat tends to be more available during the winter period. The growth of different wheat varieties varies with sowing time as each has different vernalisation and photoperiod requirement (Table 2.3). Spring wheat varieties have no vernalisation requirement and have short vegetative stage therefore are mostly sown in late autumn whereas winter types are sown in early autumn to ensure their vernalisation requirements are met (Tripathi et al., 2003). Spring varieties respond more rapidly to temperature during the season showing greater vegetative growth (leaf appearance) compared with winter types (Baker et al., 1980, Masle et al., 1989). Because winter types need vernalisation that results in longer vegetative stage, they are preferred over spring varieties for DP cropping. This gives winter types the capacity to produce more dry matter than spring-types under April or May sowing (Dann et al., 1977, Hacking, 2006). More growth with early sowing is due to a higher crown temperature followed by greater GDD accumulation between last grazing and anthesis (Harrison et al., 2015). For late sown varieties, only varieties having less GDD requirement to achieve anthesis can reach potential grain yield, enabling greater profitability (Dunphy et al., 1982, Davies, 1974).

Table 2.3. Classification of wheat varieties (Grain & Graze, 2016).

Type	**Common varieties**	**Length of growing season**	**Factors influencing reproduction**
Winter	Manning, Revenue	Long	Strong day length and strong cold period
	Wedgetail, Currawong	Mid	Moderate day length and strong cold period
Spring	Amarok, Beaufort	Long	
	Chara, Trojan	Mid	Moderate day length
	Mace, Cobra	Short	

Early sowing of winter types in Australia (e.g. February or March) extends the crop duration, lengthening the vegetative phase and benefitting biomass. Whereas later sowing (e.g. May/June) reduces fodder yield due to slower growth (Freebairn and Noad, 2002). Most studies recommend early sowing to improve forage and grain yield, whereas delays in sowing time (from recommended practice) may result in higher forage yield but at the expense of grain yield (Arzadún et al., 2006). The prolonged vegetative phase of winter types due to early sowing provides a long grazing period that increase livestock weight gain (Harrison et al., 2011a), with delays in sowing potentially affecting forage production by up to 80% (Arzadún et al., 2006).

The productivity of DP wheat depends on not only the time but also the density of sowing. Similarly, to sowing time, sowing density has both positive and negative effects on grain yield (Bonachela et al., 1995). High seeding rates (150 kg ha^{-1}) increases the forage yield whereas for better grain yield, lower seeding rate (100 kg ha^{-1}) were recommended in Pakistan (Khalil et al., 2011). Whereas, in Australia sowing rates is from 20 kg ha^{-1} for lower rainfall zones (up to 400mm per year) to 80-120 kg ha^{-1} for medium to higher rainfall zones (RIRDC, 2017). Whilst low seed rate reduces intra-plant competition and results in higher numbers of spike plant^{-1} (Ozturk et al., 2006), high seeding rate can increase spike per unit area and reduce spikes plant^{-1} (Arzadún et al., 2006). This suggests that careful manipulation of both sowing density and time are required prerequisites to attain DP potential dry matter and grain yield

2.8 Effects of grazing on crop growth, phenology and yield

2.8.1 Biomass and timing of defoliation

The biomass of a cereal crop can be used as a measure of vegetative growth. Cereal crops are generally expected to produce around 14 t DM ha^{-1} in European climates (McKendry, 2002) and 30-35 t DM ha^{-1} in Tasmania (GRDC, 2017) with good management practices from sowing to harvest.

Delaying grazing until after the start of stem elongation (GS30) (Zadoks et al., 1974) has been studied by several authors (Redmon et al., 1996, Khalil et al., 2011, Arzadún et al., 2006) and reduces grain yield by affecting dry matter remobilization from vegetative structures to the grain (Arduini et al., 2006). This means that defoliation (intensity and duration) contributes to the forage yield and its effects on latter reproductive phase results in delayed heading and lower grain yield (Khalil et al., 2011). Similarly, although protein content in grain may not affected by forage removal, in one study yield losses were 16% when forage removed at GS31 and 33% at GS31 (Royo et al., 1994). Alternatively, there is also evidence that defoliation has no effects on the grain protein and kernel diameter (Khalil et al., 2002). The investigation of dual-purpose potential of all newly introduced crop varieties before commercial release is warranted (e.g. Chapter 5).

Delaying defoliation results in lower biomass yield and delays flowering and maturity up to 10 days (Harrison et al., 2011a). Therefore, livestock should be removed from the crop according to the actual GS of the crop, not calendar date because the latter date is not indicative of GS (Dunphy et al., 1982). Prolonged grazing results in a high probability of removal of the apical meristem, which leads to a reduction in the number of viable tillers (Harrison et al., 2011a). The amount of biomass removed is related to the GS (Table 2.4) the later the crop is defoliated the more the yield penalties are and affects the farm income (Arif et al., 2015).

Table 2.4 Effect of timing of defoliation on wheat biomass (t ha^{-1}), relative yield and economic outcome (\$ ha^{-1}) compared with a grain-only crop (GRDC, 2017).

GS of grazing	Yield relative to uncut	Biomass removed	Economic outcome
25	0.89	1.2	41
28	0.90	1.7	140
31	0.62	2.3	-187

Note: GS refers to Zadoks growth stage scale at which grazing was practiced.

Wheat grain and dry matter yield is at risk of damage due to frost induced sterility and abortion of formed grains at anthesis (Barlow et al., 2015). Frost kill off the anthers or developing grain, severely limiting grain yield. Grazing allows a farmer to manipulate crop development. An effective grazing management can be frost management tool (Nuttall et al., 2017). The need to regrow will delay the timing of flowering, which might push it past the critical period when the risk of frost is highest. Early sowing enables help to establish healthy crop stand allowing grazing during tillering stage. Therefore, grazing ensures grain yield in addition to feed availability during frost period (Crimp et al., 2016).

2.8.2 Grain yield

After fulfilling the needs of livestock, crops ideally produce sufficient amount of grain yield. Yield is final product of crop growth, so all physiological and environmental conditions over the crops' life time contribute in the grain yield (Manupeerapan et al., 1992).

It has been observed that grazed crops sometime have less grain yield compared with ungrazed crops (Harrison et al., 2011a). Beside grazing stress, the grain yield also depends on the temperature exposure of the grazed crop during the reproductive stages. The potential grain yield of DP wheat depends on the availability of water (Frischke et al., 2015), temperature, and sufficient number of growing degree days (GDD) (≥ 1,000) during reproductive phase (Ledent, 1977, McMaster and Wilhelm, 1997).

Yield losses are typically observed when crops are grazed after the stem elongation (GS30) stage, whereas there are no considerable effects on grain and biomass yield when grazed before this stage (Borman et al., 2002) provided plant roots are anchored upon first grazing. Harrison et al. (2011a) observed that defoliation initiated at the early vegetative stage (GS24 to GS25) and terminated before GS31 had more beneficial effects on grain yield than terminating after GS31. Regardless of whether the crop is irrigated, or rain fed, there is often very little capacity to regrow defoliated apical meristems in determinate crops including the cereals.

2.9 Research aims

The present study firstly examines how a range of cutting strategies (removal of leaf and leaf sheath 0 to 100%) influence crop regrowth and height under the climatic conditions of Tasmania. Secondly, this study will help understand the behaviour of wheat varieties under different defoliation regimes in both controlled and field conditions. Specific aims were:

1. To evaluate the effect of low intensity Clipping and high intensity Crash defoliation strategies on plant phenology, forage production and recovery of wheat.
2. To evaluate genotypic differences in plant phenology, forage production and recovery of Australian and Chinese wheat varieties in response to defoliation under field conditions.

Chapter 3 Effect of morphological defoliation regimes on wheat regrowth

Abstract

DP wheat forage yield potential is linked with plant stature and growth habit. An experiment was established in a glasshouse at Mount Pleasant Laboratories Launceston, Tasmania during the growing season from 21 July to 19 September 2015 to study the relationship between plant structure, forage yield and crop recovery. Four wheat varieties (Tennant, Revenue, Chara and Bolac) were sown in pots. Four cutting treatments were applied at mid-tillering growth stage (GS25) to estimate forage yield. These included two ‘Clipping’ treatments which were cut at 50% and 75% of leaf length (LL50% and LL75%), and two ‘Crash’ treatments, where the entire leaf was cut from the ligule or half way along the leaf sheath (LL100% and LS50%), compared with an uncut control (C0). Total dry matter was measured by harvesting all treatments to ground level at stem elongation (GS30). Plant height was monitored at GS25, fortnightly after cutting and at GS30. Leaf chlorophyll was measured 7 days after cutting and at GS30. We found that Clipping treatments increased the height of Tennant (25% at LL50% and 17% at LL75%) and Revenue (1.8% at LL50%, 4.4% at LL75%) at GS30 compared with control treatments. Forage production at GS25 and total biomass yield at GS30 were not significantly influenced by cutting treatment or variety. Chlorophyll was not significantly affected by cutting treatment at GS30 in all varieties. This study has shown that defoliating wheat within the leaf sheath zone using Crash treatment produced greater forage yield than Clipping, but the former generally reduces final recovery and biomass. Plants of the Crash treatment were shorter at GS30 than the clipped and also had lower chlorophyll content. Like plant height and chlorophyll of LL100% and LS50% treatments were the shortest and had lowest SPAD value at GS30. We found that irrespective of growth habit, wheat plants defoliated at mid tillering can potentially produce more forage than control plants due to significant increase in plant height, provided plants are Clipped above the leaf sheath and have adequate growth resources.

3.1 Introduction

Mostly cereals, in particular wheat, are used for dual purpose (DP) cropping in many countries to provide forage during early vegetative growth and then allowed to regrow for grain production (Rodriguez et al., 1990). During vegetative growth, wheat can serve as animal forage due to its ability to grow during winter and its capacity to regrow after defoliation. Different management approaches have been developed and adopted such as the time of sowing, defoliating at specific growth stages (GSs), nutrition and stocking management during the grazing period to improve wheat DP productivity (Harrison et al., 2011c, Arzadún et al., 2006, Dove et al., 2002a, Munsif et al., 2015, Seymour et al., 2015). Winter wheat has high nutritive value with above 80% estimated *in vitro* digestibility and 22.4% crude protein (Dove et al., 2002b).

Early sowing of winter varieties and defoliation before stem elongation stage (GS30) is recommended to maximise potential forage and grain yield (Harrison et al., 2011a, Redmon et al., 1995). During the tillering stage (GS20-GS29), leaves serve as forage, as well as photosynthetic source for growth. Studies thus recommend grazing before the stem elongation stage, as this allows plants to be well anchored in the soil before grazing and encourages regrowth (Virgona et al., 2006, Harrison et al., 2011a, Kelman and Dove, 2009) and grazing should be terminated when node elongation starts because the spikes are emerging above ground level and at risk of being grazed out (Harrison et al., 2011a, Harrison et al., 2011c, Dalrymple, 1995, Dove et al., 2002a).

Walpole and Morgan (1974) reported that if greater leaf area is removed as forage it results in more grain yield penalties. Similarly, relative regrowth is related to the proportion of leaf area defoliated, Removing the whole leaf inhibits the regrowth more than clipping a portion of leaf. In other work, removing all leaves negatively affects the production of new tillers and regrowth (Brougham, 1956, Davies, 1974, Oesterheld, 1992, Richards, 1993).

Some studies define defoliation as a mechanical method of cutting plant green tissue for forage purpose (Droushiotis and Wilman, 1987). Many studies have been conducted in which defoliation was practiced by cutting at a range of heights from ground level to the top of the plant (Arzadún et al., 2006, Seymour et al., 2015). Most of these studies concluded that cutting plants at height from 0 to 5 cm high from ground level produce more forage yield, compared with clipping few centimetres from top. High forage yield from cutting close to the ground comes at the expense of later growth and development. Although the effect of cutting height on regrowth has received attention in the past but, little research has been carried out on defoliating wheat by plant morphology e.g. removing leaf and sheath entirely and in portions.

The aim of this experiment was to evaluate the effect of defoliating four wheat varieties by removing plant leaves (portion and complete) and sheath (from ligule and half) at mid-tillering (GS25) on feed dry matter production and chlorophyll content at the start of stem elongation (GS30) compared with an uncut control.

3.2 Material and Methods

3.2.1 Experiment description

The experiment was conducted in a glasshouse at the Mt Pleasant Laboratories (Long. -41.46°S, Lat. 147.14°E), Launceston, Australia. This study investigated the relationship between defoliation heights and production of feed dry matter (DM; or 'forage'). Zadoks Growth Stage (GS) (Zadoks et al., 1974) was used as a timing standard for applying treatments.

Twelve seeds of each of four wheat varieties (Bolac, Revenue, Chara and Tennant) were sown on 21 July 2015 in 12 cm diameter pots filled with a pine bark: quartz sand potting mixture. Treatments included "Clipping" (a proxy for lighter defoliation by only removing leaf proportion) and "Crash defoliation" (a proxy for heavy defoliation from ground level to the middle and end of the leaf sheath) were applied. Five treatments (four cuts and one control) were applied in three replicates on each variety at mid-tillering (GS 25). The cutting treatments were designed according to the leaf and sheath removal either in whole or in proportions (Table 3.1).

Table 3.1 Treatments applied on each of four wheat varieties in a glasshouse experiment at Mount Pleasant Laboratories during the growing season from 21 July 2015 to 19 September 2015. Abbreviations: control (Gastal and Lemaire, 2002), leaf length (LL), and leaf sheath (LS).

Treatment	Detail of defoliation	Defoliation category
C0	Control	Control
LL50%	Half of leaf length	Clip
LL75%	75% of leaf length	Clip
LL100%	Entire Leaf from ligule	Crash
LS50%	Middle of leaf sheath	Crash

The calculation for the cut point was determined by measuring mean value of three plants from each treatment pot. For example, mean value for leaf lengths of three plants above the ligule for each variety were measured (separately) as “x” cm. For application of LL50% the “x” cm was “x/2” cm. The plants were cut at point “x/2” thus defoliating only 50% of leaf length. Cutting was conducted using scissors (Figure 3.1).

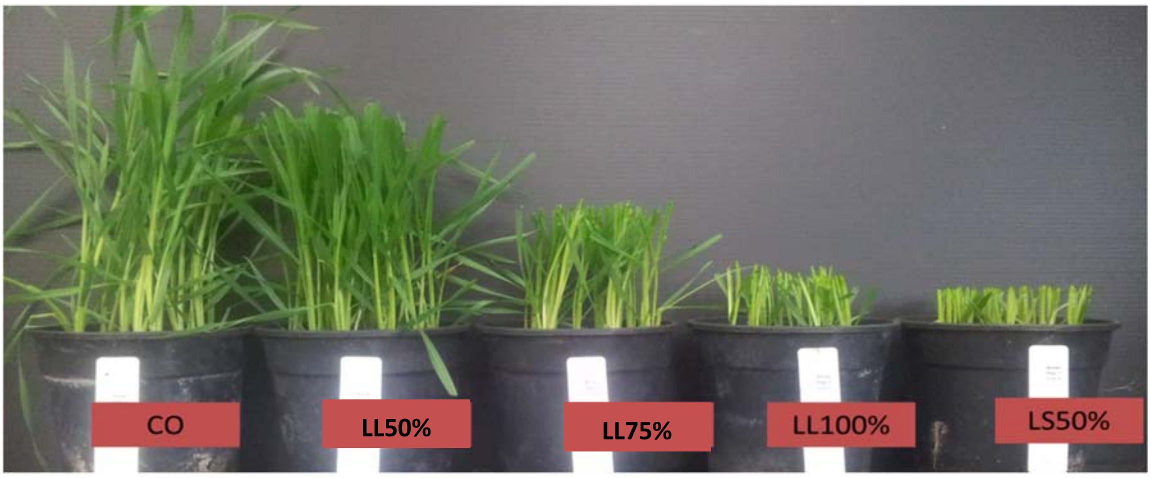


Figure 3.1. Morphological differences between cutting treatments after cutting at GS25. Abbreviations are explained in the text.

Plant height (cm) was recorded on three occasions, firstly at GS25 before taking the first forage cut, secondly 14 days after application of treatments (GS26-29) and lastly at GS30. Height was recorded by measuring from the soil surface to the top of the highest point of the plant.

Forage dry matter at GS25 and total biomass at GS30 was determined by cutting 10 plants of each treatment to the soil surface within each pot using scissors. The samples were dried in the oven at 56°C until the dry weights were stabilised.

Plant chlorophyll was recorded at seven days after GS25 and at GS30. A Minolta SPAD-502 (Konica Minolta Sensing, Tokyo, Japan) was used to quantify leaf chlorophyll content as SPAD index.

3.2.2 Statistical analysis

The significance of plant height, forage dry matter, total biomass and chlorophyll were analysed using PROC MIXED in SAS version 9.3. ANOVA was used with cutting as the treatment and varieties as another factor. Each variable was examined using quantile-quantile plots; all conformed to normality assumptions of ANOVA tests. The interaction between cutting and variety was determined using pairwise comparisons and LSD was measured using Tukey's method.

3.3 Results

3.3.1 Plant height

Main effect of varieties had significant difference (P>0.05) in plant height at GS 25, GS26-29 (14 days after cutting) and GS30. Bolac was the tallest among the four varieties at all the three stages of growth. No significant interaction was observed in the plant height at GS25 among treatments. However, significant differences (P<0.05) were observed among cutting treatments for plant height at GS26-29 and at GS30 (Table 3.2). Crash defoliation (LS50%) significantly reduced the growth compared with the uncut control.

At GS30, the interaction of varieties and cutting treatment was significant for plant height (Table 3.3). Chara and Bolac were taller than either Tennant or Revenue for the control, LL50%, LL75% and LL100% treatments. However, plant heights of all varieties were the similar under crash defoliation. Only Tennant had significantly taller plants compared with the uncut control for both LL50% and LL75% cutting treatments.

Table 3.2 Main effect of variety and cutting treatment on plant height at GS25, 14 days after cutting (GS26 – GS29) and at GS30 when subjected to four cuts and one control treatment during the growing season from 21 July to 19 September 2015 at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 3). The interaction between variety and cutting treatment at GS25 and GS26-29 was n.s.

	GS25	GS26-29	GS30
Variety			
Tennant	27.4b	35.4b	43.5b
Revenue	28.1ab	34.4b	41.4b
Chara	27.5b	39.1a	52.2a
Bolac	30.3a	39.4a	52.1a
P value	*	***	***
Cutting			
Control	29.8	42.1a	49.4ab
LL50%	28.3	41.8a	50.7a
LL75%	27.7	39.2b	50.3a
LL100%	28.7	34.8c	46.9b
LS50%	27.2	27.6d	39.4c
P value	n.s.	***	***

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

Table 3.3 Interaction between and variety and cutting regime on plant height (cm) at GS30 during the growing season from 21 July to 19 September 2015 at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 3).

	Control	LL50%	LL75%	LL100%	LS50%
Tennant	40.2fg	50.1a-f	47b-f	45.3d-f	25.3e
Revenue	43.2e-g	43.8e-g	44.9d-g	40.2fg	25.7e
Chara	58a	56.8ab	54.7a-d	51a-e	27.0e
Bolac	56.2a-c	52.1a-e	54.6a-d	51a-e	32.3de

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

3.3.2 Forage yield plant^{-1} and total biomass plant^{-1}

All treatments were cut at ground level when plants reached GS30 for estimating total biomass plant^{-1}. The main effect of variety and interaction between variety and cutting treatment were not significant ($P>0.05$). Forage dry matter plant^{-1} of the four cut treatments taken at GS25 was significantly affected by the main effects of cutting treatment (Table 3.4). LL50% and LL75% had less forage dry matter plant^{-1} compared with LL100% and LS50%, and in general, the Crash treatments produced almost 40-50% more forage dry matter than Clipped treatments.

Table 3.4 Main effect of cutting treatment on forage dry matter (DM) plant^{-1} (g) and total biomass plant^{-1} (g) during the growing season from 21 July to 19 September 2015 at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 3). Data for the main effect of variety and interaction between variety and cutting treatment were n.s.

Treatment	Forage DM GS25	Total biomass GS30
Control	NA	1.10a
LL50%	0.07d	0.93a
LL75%	0.11c	0.80ab
LL100%	0.17b	0.52ab
LS50%	0.22a	0.44c
P value	***	***

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

3.3.3 Chlorophyll content

The varieties had similar chlorophyll content even after 7 days of forage cut ($P>0.05$, Table 3.5). However, at GS30 the mean chlorophyll content was significantly different among varieties ($P<0.05$). Tennant and Revenue had a higher chlorophyll content followed by Chara while the lowest was recorded for Bolac.

Main effects were significant for cutting treatment at GS25 and GS30 for chlorophyll content. The control treatment had the highest chlorophyll content at GS25, while the lowest values for were observed for the Crash defoliation treatments (Table 3.5). At GS30, the LL75%, LL100% and LS50% treatments had similar chlorophyll content which was less than the LL50% and control treatment.

The interaction among the varieties and cut treatment was significant only at GS30 (Table 3.5). The SPAD value ranged from 31 to 50, where Tennant and Revenue plants had highest chlorophyll content in control pots and Bolac had the lowest chlorophyll when cut at LL100%.

Table 3.5 Main effect of cutting treatment on chlorophyll content (SPAD index) at 7 days after GS25 and GS30 during the growing season from 21 July to 19 September 2015 at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 3). Data for the main effect of variety and interaction between variety and cutting treatment were n.s.

	GS25	GS30
Variety		
Tennant	36.6	42.6a
Revenue	38.8	42.5a
Chara	27.57	39.3b
Bolac	30.34	36.0c
P value	ns	***
Cutting		
Control	42.9a	45.7a
LL50%	40.1ab	41.8b
LL75%	37.0bc	39.0c
LL100%	33.5cd	36.9c
LS50%	31.1d	36.9c
P value	***	***

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

Table 3.6 Interaction between variety and cutting treatment for chlorophyll content (SPAD index) at GS30 during the growing season from 21 July to 19 September 2015 at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 3).

	Control	LL50%	LL75%	LL100%	LS50%
Tennant	49.9a	40.57a-e	41.03a-e	40.4a-e	40.97a-e
Revenue	49.1ab	45.93a-c	44.17a-d	37.13c-e	36.2c-e
Chara	41.13a-e	43.57a-d	39.37b-e	38.3c-e	34.1de
Bolac	42.87a-d	37.37c-e	31.43e	32e	36.37c-e

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

3.4 Discussion

Plant height of all varieties was different at mid-tillering (GS25) and 14 days after cutting indicating that all varieties had different growth type, where. Bolac and Chara were taller compared with Revenue and Tennant. This is likely because Bolac and Chara are tall statured, early maturing varieties and regrow faster than the medium statured, late maturing Revenue and Tennant as biomass and time of maturity is related to photoperiod and vernalisation (Harris et al., 2017).

Heights at terminal spikelet (GS31) suggested that Clipping treatments were taller than Crash treatments. It has been observed in many experiments that Crash grazing typically removes plant tissue down to or more than a critical point of the meristem, which significantly affects regrowth capacity in wheat but has also been observed in broad leaf crops and canola (Dann, 1968, Redmon et al., 1996, Kirkegaard et al., 2012). The amount of photosynthetic tissues removed with Clipping is less than that removed for the Crash treatment, and so the recovery of plants with leaves removed as opposed to leaf sheaths significantly influenced regrowth capacity (Seymour et al., 2015). Ledent (1977) studied removal of lamina, complete leaf and proportions of leaf. He reported that removal of complete leaves reduces whole plant photosynthesis by 25-28%, which was further reduced by 24-30% on the removal of flag leaf. Similarly, Davies (1974) also defoliated the plant according to the structure and it was observed that above-ground regrowth was dependent on the amount of residual leaf mass. It was also observed that as the proportion of defoliated leaf was increased it affected the regrowth as well as initiation and growth of tillers.

When comparing the chlorophyll content of the cut treatment with control after 7 days of forage cut at GS25 we observed that cutting below the leaf sheath significantly reduced the chlorophyll content. Crash treatments had a lower chlorophyll content than Clip treatments and control, which might be due to less time to recover for adequate photosynthetic biomass removed strongly suggesting that the regrowth and development of defoliated plant depends on the residual biomass. Asghar and Ingram (1993) applied treatments listing defoliating all leaves, two leaves and flag leaf, they found significant effects on the N content that were reduced by up to 17.3% in grain yield (with increasing defoliation intensity). Subba Rao et al. (1989) divided plant parts into two categories foliar and non-foliar, and described stem, ear and leaf sheath as non-foliar parts. They found that if wheat plants were Clipped and only foliar parts are removed, then non-foliar parts contributed 36-51% towards regrowth in latter reproductive growth and development.

It is possible that Clipped plants had more leaf tissue for photosynthesis to overcome grazing and recover growth processes, whereas the plants of the Crash treatments used the reserves in the stem to survive defoliation but had insufficient for full regrowth of photosynthetic tissue (Davies, 1974). Ourry et al. (1988) observed that nitrogen (N) was initially remobilized from roots and stem to new leaves during the first six days after clipping while in the second phase after six days the regrowth occurs provided there is mineral nitrogen from the growth medium or soil. The volume of nitrogen mobile reserve depends on its utilization during growth and is generally cycled in plant (root → shoot → root → shoot) (Simpson et al., 1982). Skinner et al. (1999) also showed that total non-structural carbohydrate reserves (TNC) and nitrogen stored reserves mainly in roots and crowns of plant are remobilized to play a role in early regrowth after defoliation. Therefore, results in this study indicate that control and clipped plants had more reserves of TNC and N than Crash defoliated plants since more chlorophyll was found in control and clipped treatment at terminal spikelet (GS31). However, additional experiments would be needed to support this claim.

Defoliation of the leaf and sheath at GS25 resulted in different forage yield plant^{-1}. Crash defoliation yielded more forage compared with clipped due to the increased intensity of cutting (Arzadún et al., 2006). Seymour et al. (2015) recorded 0.3 tha^{-1} of biomass removed in wheat when clipped before the start of stem elongation (GS30) and recommended Clipping of spring type crops for Western Australia. We observed that he regrowth of defoliated treatments depends on the remaining plant biomass. Richards (2000) and Ehdaie et al. (2006) stated that assimilate storage is function of stem and carbohydrates stored in stem and translocated afterwards. Therefore, Clip defoliated plants regrowth was more than Crash defoliated as Clipped have more stem mass left over after defoliation. Similarly, Clipped plants may have had greater carbon (C) and N reserve mobilization than Crash defoliated plants, the former yielding more regrowth (Gastal and Lemaire, 2015).

In our study the total biomass yield in Crash treatment was twofold lower than that of the control and Clipped treatments. It was evident that Clipped winter wheat reduced plant height compared with the uncut control which may also be related to the time of defoliation (Cutler et al., 1949, Gutman et al., 2001). The results revealed that total biomass depended on the amount of leaf area removed as forage. Clipped treatments produced 50% less forage yield than Crash treatments but had an inverse relation for biomass plant, indicating that residual leaf area (or leaf area remaining after forage cut), contributed to regrowth. García del Moral (1992) reported a loss in leaf area index due to cutting and that the decrease in green leaf area effected growth after defoliation through to maturity. Similarly, Sharrow (1990) reported that the GS at which the crop is defoliated and the time duration spent to regrow plays a more important role in recovery and regrowth than defoliation intensity.

We observed that the defoliation of all varieties at mid tillering (GS25) in the glasshouse gave a good estimate of the forage yield but did not differentiate between varieties. In DP wheat production it has been observed that grain yield is dependent on the defoliation time and intensity (Harrison et al., 2011a), which is consistent with these results. If the defoliation strategy is optimum plant will have better regrowth opportunity to support all the reproductive stages sufficiently to ensure optimal grain yield. Further, forage removal in early vegetative stage is likely to increases grain yield because crop recovers faster and ensures more leaf area at anthesis which is considered crucial for maximum grain yield (Redmon et al., 1995).

3.5 Conclusion

Cutting height has significant importance when determining DP productivity under controlled conditions (Glasshouse). The results of defoliation treatment for both Crash and Clipping revealed that

1. Wheat plants should be Clipped during early vegetative stage
2. Removing leaves in proportion or completely to the point of first leaf ligule enables rapid recovery resulting in better regrowth (plant height) and biomass compared with removal of all leaves and half the leaf sheath.
3. Tall stature varieties recover more rapidly if Clipped in early vegetative stage.

This experiment gave a clear indication how defoliation tolerance of plant is related to its morphology and structure. However there remains a need to relate these results to a specific height to practically apply this strategy in the field on number of varieties that differ in growth habit and type, which is examined in Chapter 4.

Chapter 4. Effect of different cutting heights from ground level on recovery of wheat in field conditions.

Abstract

An experiment was established in the field at Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 2 October to 30 November 2015 to study the effect of cutting height on forage yield and crop recovery. Three wheat varieties (Revenue, Bolac and CS170) were planted in the field. Five cutting treatments were applied during tillering (GS25) to estimate the forage yield. Treatments included Crash (cutting at 0, 3 and 5 cm above ground level) and Clipping (cutting at 8 and 10 cm above ground level) compared with an uncut control. Total dry matter was measured by cutting all treatments to ground level at terminal spikelet (GS31). Plant height was monitored at GS25 and at GS31. Chlorophyll was measured at GS25 (before cutting) and at GS31. Results showed that Clipping treatments did not affect the height and biomass compared with the control, while the Crash treatment significantly decreased height at GS31. Forage production at GS25 was significantly influenced by cutting, where Crash treatments removed more forage and left less residual biomass that affecting the regrowth and resulting in lower plant height and total biomass at GS31. Cutting showed no significant effect on chlorophyll, however varieties varied significantly for their chlorophyll content at GS31, with CS170 being greener than Bolac and Revenue. The biomass yield of Crash defoliated plants was 50% less than control, whereas Clipped plants had more than 50%. This study has shown that defoliating wheat during mid tillering at heights up to 5 cm reduced the plant biomass and regrowth. Irrespective of growth habit, defoliating above 5 cm enabled plants to utilise residual biomass for latter growth so that they can recover similar to uncut plants. From this experiment we conclude that beside higher forage yield Crash defoliation discourages plant regrowth and potential to regain biomass.

4.1 Introduction

Wheat is an important dual purpose (DP) cereal crop that is typically `grazed in its early vegetative stages to allow the crop to regrow before being harvested for grain at maturity (Virgona et al., 2006). Like other cereals, wheat's capacity to provide forage and regrowth for the grain productivity depends on defoliation management practices (Redmon et al., 1995).

DP wheat defoliation is generally recommended to commence at tillering (GS25) as younger plants are prone to being pulled out when grazed (Harrison et al., 2011a). Clipping/cutting wheat before the stem elongation stage (GS30) can provide highly nutritive forage effective to fill the winter feed gap (Tian et al., 2012). Moreover, defoliation before stem elongation encourages better regrowth to produce greater forage and grain yield compared with cutting at the first and second node stage (Miller et al., 1993). The quantity of biomass in DP wheat increases the GS progress from tillering toward stem elongation stage (Harrison et al., 2011a). For example, the *in vitro* digestible dry matter (IVDDM) concentration of wheat forage decreases from 80 to 58% and cell wall constituents (CWC) and acid detergent fibre (ADF) concentrations is higher before the flag leaf stage, whereas acid detergent lignin (ADL) concentration increases linearly with increased maturation (Cherney and Marten, 1982). This change in quality of forage impacts on liveweight gain of livestock. For example, Dove et al. (2002a) studied two wheat varieties (winter and spring) along with other cereals as forage for young sheep and found that the sheep grazing winter wheat gained more live weight than sheep grazing other cereals.

As discussed in previous chapters, experiments on DP wheat can use either use livestock or simulate grazing using mechanical defoliation. The advantage of mechanical defoliation is that it mitigates the potential confounding effect of livestock trampling the crop. Wheat defoliation can be termed as "Crash" or "Clip" depending on the intensity of removal of green tissue. Crash defoliation refers to the heavy defoliation intensity leaving ≤ 5 cm residual plant tissue whereas Clip defoliation refers to lighter defoliation intensity ≥ 5 cm plant tissue (Seymour et al., 2015). Clipping or grazing of leaves below a critical limit of leaf area results in utilization of assimilates from the primary stem. Arzadún et al. (2006) found that Crash defoliation of wheat (around 3 cm) provides 21% more forage when Clipped (7 to 8 cm) before stem elongation stage. Arzadún et al. (2006) found that a defoliation height of 3 cm compared with Clipping at 7 cm produced more forage yield, but the latter growth and grain yield was negatively affected. They also observed that varietal differences affect forage yield and recovery potential possibly due to difference in variety growth habit and growth type.

Forage yield depends on two main factors, height of defoliation and time or GS of defoliation. Seymour et al. (2015) reported that Clipping (≥ 5 cm) produced less forage yield than Crash (≤ 5 cm) with having no or minimum effects on regrowth and grain yield. In contrast, Dunphy et al. (1982) observed that Clipping wheat (7.5 cm) before early joint stage produces less forage yield than at mid and late joint stage but significantly higher grain yield than the two latter stages. Davidson et al. (1990) cut wheat and other cereals to 1 cm height at different intervals up until developing ears were observed above ground level and recommended that defoliation of wheat grown in cooler environments can be practiced until the stem elongation stage. The studies show that forage yield is a product of defoliation strategy and GS (Arzadún et al., 2006, Harrison et al., 2012a).

In Chapter 3, plant defoliation was linked to plant morphology and GS. Defoliation was based on removal of leaves and leaves plus sheath at GS25. Varieties of wheat with tall, medium and prostrate growth habit were quantified for height, forage yield, biomass and chlorophyll in glasshouse conditions. The result of the previous experiment enabled an understanding of the effect of defoliation on plant recovery according to plant structure. To relate these results with positional cutting (mechanical defoliation at a specific height above the soil surface), this experiment was designed to study the effects of defoliation height at the same tillering stage (GS25) under field conditions. The experiment was part of preliminary study for selecting a single cutting height to be applied on a large number of wheat germplasm selections in the field. Treatments were evaluated based on plant height, forage, biomass yield and chlorophyll.

4.2 Material and Methods

4.2.1 Experiment description

An experiment was conducted at Mount Pleasant Laboratories (Long. -41.46°S, Lat. 147.14°E), Launceston, Australia. Wheat varieties were observed from sowing (2 October) to stem elongation (30 November) in the field to evaluate their response to different cutting heights. Three varieties with five cutting treatments and a control with how many replicates was sown in a randomized complete block design. Twenty seeds were sown in one row (plot size =1 m long x 1.5 m wide). NPK was applied at 120:100:100 kg/ha in the form of urea (28 g/plot), di-ammonium phosphate (112 g/plot) and muriate of potash (45g/plot).

The wheat varieties Revenue and Bolac (medium growth habit) and CS170 (prostrate) were selected to observe responses to different cutting heights measured from the ground listed in (Table 4.1).

Five cuts and one uncut treatment were applied when the crop reached mid tillering (GS25). The cutting treatments were designed according to the plant height from ground level. “Clipping” (a proxy for lighter defoliation by only removing leaf segments 5 cm above from ground level) and “Crash defoliation” (a proxy for heavy defoliation from ground level to 5 cm) were applied. Hand cuts were taken by using a sickle.

Table 4.1. Treatments applied on three wheat varieties in a field experiment conducted at Mount Pleasant Laboratories from 2 October to 30 November 2015.

Treatment	**Cutting height (cm) measured from ground level**	**Defoliation Category**
C	Uncut	Control
C0	0 – whole plant cut	Crash
C3	3	Crash
C5	5	Crash
C8	8	Clip
C10	10	Clip

Plant height (cm) was recorded on two occasions, firstly at mid tillering stage GS25 before the forage was cut, secondly at stem elongation stage GS31 before the total biomass cut. Plant height was recorded by measuring plant height from the ground to the tip of the tallest leaf.

Forage dry matter (g) was measured by cutting 20 plants within each treatment plot. Similarly, for total biomass per plant the plants were harvested from ground level. The samples were dried in an oven at 56°C until the dry weights were stabilised and then weighed.

Chlorophyll of three fully emerged leaves was recorded at GS25 and GS31. A Minolta SPAD-502 (Konica Minolta Sensing, Tokyo, Japan) was used to quantify leaf chlorophyll content as SPAD index.

4.2.2 Statistical analysis

The significance of plant height, forage dry matter, total biomass and chlorophyll were analysed using PROC MIXED in SAS version 9.3. ANOVA was used with cutting as the treatment and varieties as another factor. Each variable was examined using quantile-quantile plots; all conformed to normality assumptions of ANOVA tests. The pairwise comparisons and LSD was measured using Tukey's method.

4.3 Results

4.3.1 Plant height (cm)

Plant height at GS25 (before forage cut) showed that the wheat varieties Bolac (27.9 cm) and Revenue (25.0 cm) were significantly ($P<0.05$) taller than CS170 (18.5 cm).

The main effect of cutting and the interaction between cutting and variety at GS25 was not significant ($P>0.05$). The interaction between variety and cutting treatment was significant at GS31 (Table 4.2). CS170 being dwarf to semi dwarf was greatly affected by forage cut and had the shortest plant height compared with Revenue and Bolac for all cutting treatments. Plants of uncut control and Clipping (10 and 8 cm) had the highest plant height. Cutting whole plant and 3 cm had the lowest plant height.

Table 4.2 Interaction between variety and cutting height for plant height (cm) at GS31 during the growing season 2 October to 30 November at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 4).

	Cut height (cm)					
	Control	**0**	**3**	**5**	**8**	**10**
GS31						
Bolac	55a	40.7b-e	43.3bc	45.9b	53.4a	55.3a
Revenue	40.2b-e	32.6f-g	34.6e-g	37.4c-e	36d-g	41.4b-d
CS170	35.3 d-g	29.8g	33.1fg	35.4 d-g	35.6d-g	33.9e-g

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

4.3.2 Forage dry matter plant^{-1} and total biomass plant^{-1}

There was a significant interaction between variety and cutting height for forage dry matter plant^{-1} at GS25 (Table 4.3). Crash treatments had higher forage dry matter than Clip treatments, except mean values of cutting at 5cm and 8 cm which were not significantly different. As expected Cutting at 0 cm (whole plant cut) resulted the highest forage yield. The lowest forage yield was recorded for Clipping at 8cm and 10 cm, and the latter was more than 50% less than cutting at 0 cm height. Bolac and Revenue when defoliated at ground height and 3 cm produced greater dry matter plant^{-1} than other CS170 and there was no difference at other treatments.

For total biomass plant^{-1} at GS31, the greatest total biomass yield was recorded in the uncut control followed by the Clip cutting at 5, 8 and 10 cm (Table 4.4). Not surprisingly, cutting the whole plant or at ground level (0 cm) had significantly lowest total biomass yield as plant recovery was slow.

Table 4.3 Interaction between variety and cutting height for forage dry matter plant^{-1} (DM) at GS25 during the growing season 2 October to 30 November at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 4).

	Cut height (cm)					
	Control	**0**	**3**	**5**	**8**	**10**
Forage DM Pl^{-1} (GS25)						
Bolac	NA	0.54a	0.44ab	0.35bc	0.27cd	0.22c-e
Revenue	NA	0.46ab	0.37ab	0.29cd	0.18d-f	0.13e-g
CS170	NA	0.23c-e	0.16d-f	0.20d-f	0.15d-f	0.10fg

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

Table 4.4 Main effect of variety and cutting height for total biomass plant^{-1} (g) at GS31 during the growing season 2 October to 30 November at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 4).

Treatment	GS31
C	4.04a
0	0.79d
3	1.63c
5	1.96bc
8	2.49b
10	2.38b
P value	***

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

4.3.3 Chlorophyll content

The main effect and interaction between variety and cutting treatment were not significant at GS25 (P>0.05), with an average value across treatments of 45.8 SPAD units. .

There was a significant interaction between variety and cutting height at GS31 (Table 4.6). Clipping CS170 at 5, 8 and 10 cm had the highest chlorophyll content similar to the SPAD value for Revenue and Bolac at 10 cm. cutting whole plant affected the leaf regrowth and had showed less SPAD value at GS31.

Table 4.5 Interaction between variety and cutting height for chlorophyll content (SPAD unit) at GS31 during the growing season 2 October to 30 November at TIA, Mount Pleasant Laboratories, Launceston, Tasmania (See ANOVA table in Annex 4).

	Cut height (cm)					
	Control	**0**	**3**	**5**	**8**	**10**
GS31						
Bolac	48.6a-c	39.5e	47.3b-d	46.2b-e	46.7b-e	49.4a-c
Revenue	45.2b-e	40.2de	46.7b-e	45.7b-e	44.3b-e	50.2ab
CS170	45.4b-e	41.6c-e	50.2ab	51.4ab	56.1a	52.4ab

Note: Means of each variable followed by same letter are not significantly different (P=0.05).

4.4 Discussion

Defoliation affected plant height and biomass yield. Each variety had a different capacity to tolerate defoliation and therefore a different capacity to effect regrowth (Dunphy et al., 1982, Miller and Donart, 1979). Plant capacity to respond to defoliation is also dependent on other factors like time of recovery and soil nitrogen (N availability) (Ferraro and Oesterheld, 2002).

All varieties behaved according to their growth habit in terms of plant height at GS25, which is a good indicator if we were to evaluate the defoliation treatment effects in further studies involving a range of introduced germplasm. There were significant height differences due to cutting treatments at GS31. Bolac being the tallest and CS170 was shortest due to the prostrate growth habit.

A significant interaction between variety and cutting treatment was observed for plant height at GS31. Clipping at 8cm, 10 cm and the control plots achieved the same plant height followed by cutting at 5 cm height. It is evident that plant recovery time is proportional to the intensity of forage cutting. Therefore, cutting at ground level reduced the height of all varieties, indicating that it may be too severe, and plants may not have the necessary energy to regrow optimally for grains. These results are in line with Seymour et al. (2015) who reported that cutting 5 cm above ground level before the commencement of reproductive growth did not affect the growth and grain yield compared with defoliation below 5 cm height or at ground level. It was observed that the height at GS31 of plants defoliated at 5cm or less was shorter than control and all varieties behaved according to the growth habit e.g. Bolac was mostly taller than Revenue before and after cutting. Moreover, the difference in height of control and cut at GS31 due to the imposition of cutting treatments may be because cutting removed the apex and new shoots could not reach the same height due to a shorter regrowth time. Defoliation according to height from the ground was also practiced by Arzadún et al. (2006) and Noy-Meir and Briske (2002), who observed similar response of residual wheat biomass to regrowth.

All the varieties defoliated at GS25 had different forage yields, due to a significant interaction between variety and cutting treatment. Bolac, being erect and tall, produced the highest forage DM plant^{-1} and CS170, being prostrate and short, produced half the forage yield compared with the other two varieties. Beside the varietal characteristics influencing the forage yield the height of cutting also significantly affected the forage yield. The Crash defoliation yielded more forage than Clipped plants. Davies (1974) found that Crash defoliation resulted in better forage yields and if the crop is defoliated at early vegetative stages there is potential for a second forage cut before the crop enters the reproductive phase. Once the crop starts stem elongation, no further forage cutting is recommended because this may damage the reproductive meristem. Arzadún et al. (2006) found that cutting plants at 3 cm height produce more forage yield than cutting at 7 cm.

The biomass yield was affected by cutting treatment. Crash treatments had lowest biomass at GS31 compared to Clipped treatments. Total biomass was significantly related to the defoliation height. Plants defoliated above 5 cm produced less forage yield at GS25 but more total dry matter at GS31. Thus, the more photosynthetic tissue remained on the plant resulted in better growth and development of the plant as compared with Crash defoliation. Harrison et al. (2011a) reviewed several studies and concluded that treatments which were grazed for shorter period and defoliated before GS31 had more residual photosynthetic tissue compared with treatments defoliated for longer period and high intensity, and this enhanced regrowth and grain yield. This may be due to less or no damage to apical meristem during defoliation.

After defoliation the remaining leaf and new emerging leaves receive carbon reserves, thus regrowth of the plant and rate of newly emerged photosynthetic tissues will be the measure of carbon reserves (Visser et al., 1997). The amount of the dry matter removed under each treatment shows that Crash defoliated plants are more stressed in recovery due to the lack of green photosynthetic tissue, such that the recovery time is more than the Clipped plants. The defoliation reduces the biomass by nearly 50% in Clip and almost by 90% when defoliated at ground height level. Clipped plants showed better biomass plant^{-1} than wheat defoliated at ground height level but were all still substantially lower than the control unclipped plants (Sharrow, 1990, Davies, 1974).

The chlorophyll content of three varieties at GS25 was not significantly different before defoliation. The response to defoliation at GS31 on chlorophyll content varied among varieties. The prostrate variety CS170 was observed to be greener in colour than the other two, especially during the recovery stage. This might be due to prostrate habit of CS170 having shorter and higher quality canopy (more N / g DM), better root growth. and better photosynthetic activity as compared with tall or medium varieties Bolac and Revenue. Similarly, defoliation at different heights affected the chlorophyll content at GS31, which changed according to cutting height. Ledent (1977) showed similar findings where regrowth potential of the plant depended on the amount of green leaf available for photosynthesis.

4.5 Conclusion

Moreover, defoliation severity significantly affected plant growth and development. Taller varieties (Revenue and Bolac) recovered better than prostrate type CS170 but only in terms of height. Our results indicated that Crash defoliation (cutting at ground height level or at 3 cm) may not be recommended as they provided more forage yield but at the expense of regrowth. However, cutting at 5 to 8 cm may be suggested in DP wheat cropping since this ensured sufficient leaves and biomass remaining for regrowth, increasing the biomass needed to complete reproductive phase for grain production. We envisage that defoliation at 5 cm can be the most appropriate height to further evaluate DP potential of wheat since cutting at this height should retain sufficient residual biomass for adequate regrowth.

Chapter 5. Growth and development of wheat genotypes as affected by a single cutting strategy

Abstract

Improved dual-purpose (DP) production is possible by selecting genotypes that respond to appropriate pre- and post-defoliation management for adaption to local climatic conditions. To evaluate genotypes that have potential to produce forage during winter and recover to produce grain yield in Tasmania, a field experiment was established at Mount Pleasant Laboratories in Launceston from 10 March to 30 September 2016. The genotypes selected in this experiment were long season winter types of tall, intermediate and prostrate growth habit previously unexamined for DP productivity. Two levels of treatments (control and cut at 5 cm at GS31) were applied. Calendar days, plant height (cm) and GDD (ºCd) were observed for GS01, GS21, GS31 and GS45. The number of tillers (per plant, number of leaves per main stem, forage yield (t ha^{-1}) and total biomass yield (t ha^{-1}) were recorded at GS31. All the genotypes except one new variety (73/44) reached GS21 at same the time but there were significant differences among genotypes in plant height, forage yield, calendar days taken, and GDD accumulated at GS31. Genotype H-051 was tallest in plant height (46.6 cm), with more forage (2.23 t ha^{-1}) and biomass yield (3.39 t ha^{-1}). Cutting was applied when genotypes reached GS31. All the genotypes were significantly affected by cutting treatment. Genotypes H-061 and Mackellar showed the greatest potential regrowth capacity by attaining a height (60 and 64 cm, respectively) similar to control. In contrast, H-220 and H-207 accumulated less GDD (1412 and 1468ºCd, respectively) compared with other genotypes to reach GS45. The genotypes that reached GS45 earlier were shorter than genotypes accumulating higher GDD. The correlations revealed that the genotypes having higher number of leaves on main stem, tillers plant $^{-1}$ and days taken to reach GS31 had higher forage and biomass yield. As this study was concluded at GS45, further studies are recommended to evaluate the potential of these promising genotypes for grain yield evaluation.

5.1 Introduction

The potential of wheat as Dual-purpose (DP) crop has been studied extensively. Majority of past work examined the relationship of DP at different sowing times (Arzadún et al., 2006), defoliation (Fulkerson et al., 1999), GS (Harrison et al., 2011a, Harrison et al., 2012b, Kelman and Dove, 2009), cutting heights (Binnie and Harrington, 1972, Dovel, 1996) and variety or genotype (Hacking, 2006). Each of these factors effects growth and development of DP wheat that may also vary under different agro-ecological zones.

The performance of DP genotypes is measured by the quantity of forage produced, regrowth potential and grain yield. As discussed in Chapters 3 and 4, the GS at defoliation is a critical issue in DP cropping. Previous studies have confirmed that a wheat crop should only be defoliated for forage once it is well anchored in the soil from mid-tillering (GS25) up to the early stem elongation stage (GS 25-31) (Harrison et al., 2012b, Redmon et al., 1996). It was observed that cutting plants at a height of 5 cm from ground before the start of stem elongation (GS31) has less impact on plant growth and development compared with cutting after this stage (Seymour et al., 2015).

The response of wheat genotypes to defoliation varies according to the growth habit, growth type and the agro-climatic condition in which they are cultivated (Nicholson, 2006, Tripathi et al., 2003). Winter and spring wheat have differed in tolerance to defoliation, depending on sowing time, defoliation (time and intensity) and climatic conditions (Carver et al., 2001). But, differences in vernalisation and GDD (Growing Degree Days, also referred as Heat Sums or thermal time) to maturity causes variation in DP productivity of cereal crops (Chouard, 1960, Weir et al., 1984, Edwards et al., 2007), which are accentuated under defoliation stress when plants need to redistribute assimilate to promote reproductive development (Manupeerapan et al., 1992). For optimum forage and grain yield, knowledge about varietal response to defoliation is required to identify new germplasm with improved regrowth potential.

The purpose of this experiment was to evaluate the DP potential of 99 wheat genotypes using the Clipping defoliation strategy identified in Chapters 3 and 4. Most genotypes were long-season wheat originating in China and Australia, with a wide range of growth habit (Annex 1).

5.2 Materials and Methods

5.2.1 Location and climate

The experiment was conducted in 2016 in the field at Mount Pleasant Laboratories, Launceston (-41.46°S, 147.14°E). Mean monthly temperature and rainfall data from sowing to maturity during the growing season were obtained from Bureau of Meteorology (Bureau of Meterology, 2016).

5.2.2 Temperature, rainfall and Potential evaporation

The total rainfall recorded from January-September 2016 was 600 mm, with average air temperatures ranging from 7 to 18ºC (Bureau of Meterology, 2016). To maintain growth, an additional 310 mm of irrigation was applied during the growing season, mostly during March and April, but some also in August and September (Figure 5.1c). Potential evaporation is referred to the amount of water which evaporates from an open evaporation pan with no control on water supply (Figure 5.1 b). The potential evaporation was at peak during sowing month (March) and showed a decline till June but gradually inclined during latter months.

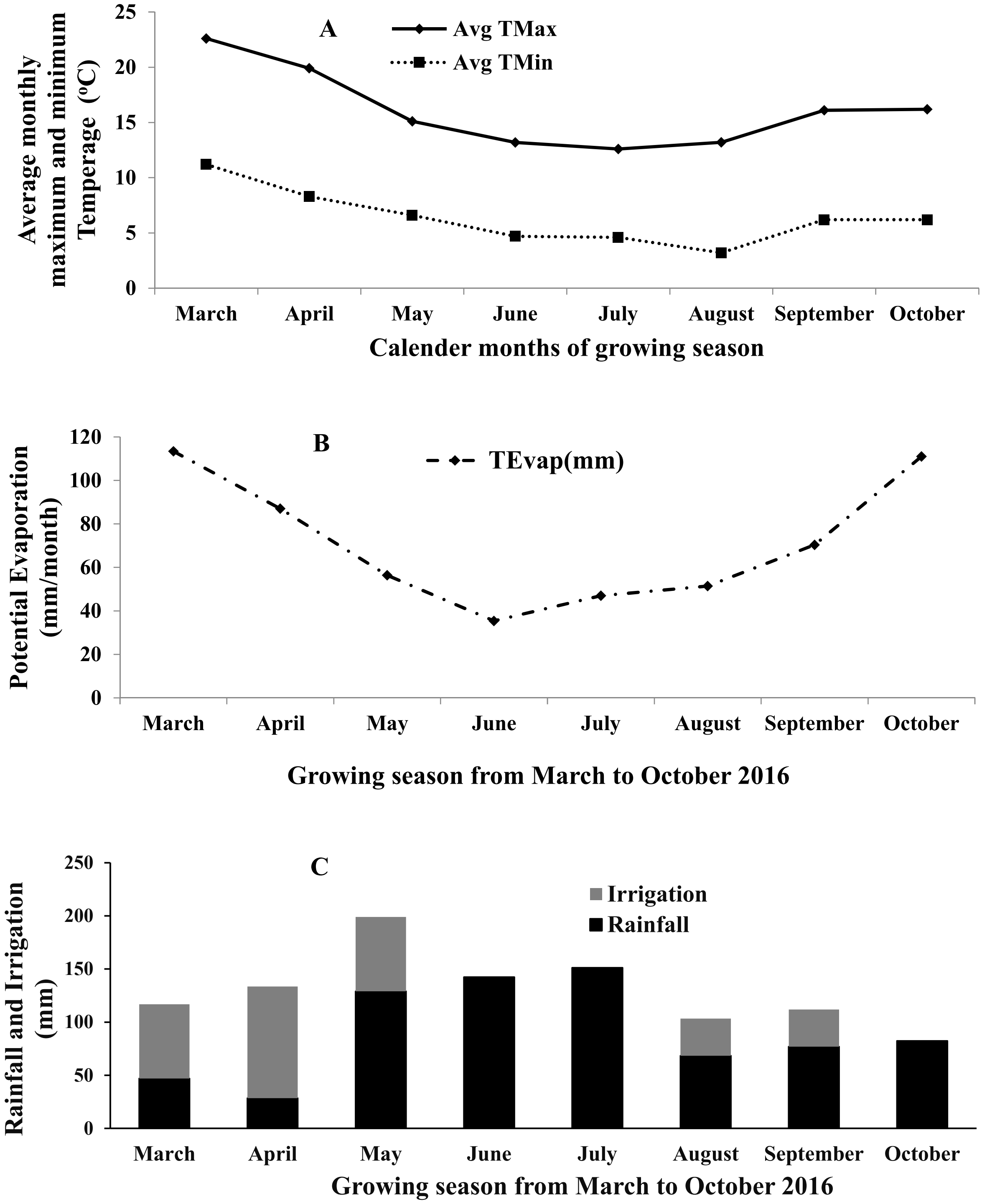


Figure 5.1. (A) Average monthly temperature maximum and minimum (ºC), (B) Potential evaporation (mm), (C) Total monthly rainfall and irrigation (mm) during the growing season from 10 March to 30 September 2016 at Mount Pleasant Laboratories, Launceston, Tasmania.

5.2.3 Experimental design and site details

The experiment was conducted in a randomized complete block design (RCBD) using a split plot arrangement with three replications. Each plot (genotype) was split into two subplots, control (no Clipping) and treatment (Clipping at GS31). Each plot had four rows at 15 cm spacing. One row of each treatment plot was designated for forage dry matter cut at 5 cm height and the second was cut to estimate the total biomass (cut at ground level) at GS31. The cutting treatment was applied at GS31 because it is can be predicted by observing the first node appearance and defoliation could be managed as all the 99 genotypes did not reach GS31 at same time. Secondly, the forage yield potential of these new genotypes could be better estimated at first-node detectable stage.

The site had been in pasture since 2014. Soil fertility tests were carried out to identify any nutrient deficiencies. Soil samples were taken from a depth of 0-30 cm and were analysed by AGVITA Analytical Pty. Ltd. Lime was applied at the rate of 2.5 t/ha. Fertilizer "Yara Mila" manufactured by Yara International ASA was applied at a rate of 250 kg/ha having N: P: K of 12:5:15. All P was applied at the time of sowing. An additional 50kg/ha of N was applied as urea (granular form) with the first irrigation (sprinklers) of approximately 35 mm about 15 days after sowing, another 50 kg/ha of N was applied after cutting. Plants were irrigated as required. The following chemical herbicides were applied to control broad leaf and grass weeds: Preemergent Boxer Gold 1.7L/ha, broadleaf herbicide Bromocide (200g/L Bromoxynil) for broad leaf weeds at the rate of 1 Lha^{-1}; Canvas (750 g/l MCPA) at the rate of 1L ha^{-1} at GS24, and Puma Super (69g/L Fenoxaprop-p-ethyl) were applied at the 1.25 L ha^{-1}. Porsaro (420 SC) fungicide was used at the rate of 400 ml ha^{-1}.

5.2.4 Sowing and plot size

Hand sowing was carried out after conventional tillage on 10 March 2016, which is a typical time for sowing DP wheat in northern Tasmania (Miller et al., 2010). Four rows of each genotype were sown in 0.6 m^2 plots (10 seeds evenly-spaced per row). The beds were raised and sloped to drain excess water.

5.2.5 Genotypes

The 99 genotypes used in the experiment were long season (winter, intermediate and late spring) (Annex 2) selected from a larger collection of 300 exotic Chinese and Australian genotypes held by the Tasmanian Institute of Agriculture. Most of the genotypes have not been evaluated for forage productivity or regrowth potential and exhibited diversity in growth habit (tall, erect and prostrate).

5.2.6 Defoliation strategies

In Chapter 3 and 4 cutting at the end of leaf sheath and 5 cm, respectively, had the best regrowth after defoliation compared with the other cutting treatments. Therefore, on the basis of these findings, it was decided to defoliate the 99 genotypes in this chapter at 5cm height from ground level. Moreover, leaf sheath of most genotypes is below 5cm and cutting below 5cm affects regrowth.

5.2.7 Crop phenology and growth

Phenological parameters were measured when 70-80% of the plants in a plot reached, the start of tillering (GS21), stem elongation (GS31) and mid booting (GS45). Calendar date was recorded from sowing to emergence (GS01), tiller initiation (GS21), stem elongation (GS31) and mid booting (GS45) for each plot. Days to GS45 were recorded from sowing to mid-booting (when 70 to 80% boots were swollen).

GDD calculations were made by using three cardinal temperatures, comprising 0ºC as a base, 26ºC as optimum and 34ºC as a maximum (McMaster and Wilhelm, 1997). The effect of cutting on GDD to each GS was measured by calculating GDD from sowing to the GS01, GS21. GS31 and for GS45 cut and control separately. Number of leaves and tillers were recorded at GS31 and plant height was measured at both GS31 and GS45.

5.2.8 Dry matter

The dry matter was estimated when forage yield was measured by cutting the plants at a height of 5 cm from ground level upon reaching GS31. Total biomass yield was measured by cutting plants to ground level at GS31. The cut plant material of both forage and biomass was dried at 56°C in an oven until weight was stabilised.

Originally, we designed the experiment to cut (according to the treatments) and then to harvest for grains. Unfortunately, the sheep from adjacent paddock broken into the experiment and compromised its integrity. Therefore, we are unable to present grain yield data. Therefore, the experiment was terminated and results were drawn based on available collected data.

5.2.9 Data analyses

The significance of plant height, forage dry matter and total biomass was analysed using analysis of variance (ANOVA) with SAS version 9.3 (Annex 5). Upon examining using quantile-quantile plots, all variables conformed to the ANOVA assumptions of normality. The experiment was analysed as a split plot design with three replicates, one (main) treatment and another (sub) factor, genotypes, with 99 levels. The P value for the F tests (Pr > F) indicates if the effect is significant.

5.3 Results

5.3.1 Phenological parameters

There were differences among genotypes for days to emergence (GS01) (P= 0.001), but not days to tiller initiation (GS21) (P>0.05). Days to forage cut (GS31) and days to booting (GS45) were significant among genotypes. The main effect of cutting treatment and the interaction between cutting treatment and genotype were not significant.

The days taken to GS01 ranged between 6.3 to 8.3 days (Figure 5.2). Earlier emergence was observed for genotypes CS170 and H-020 (6.3 days), compared with the other genotypes. The control genotypes Mackellar and Revenue took 8 days to emerge.

Days to tiller initiation (GS21) were not significantly different overall, though genotype 73/44 took the longest time (36 days) to initiate tillers. The other genotypes averaged between 25.6 to 31.6 days.

Considerable differences were noted among genotypes for days to GS31, ranging between 52 to 136 days across genotypes (Figure 5.3). Early attainment of GS31 was observed between 53 to 97 days for many genotypes including H-189, H-229, H-233, H-74, WL-Wheat, H-237, Revenue, SW95-50292, and several others. In contrast, H-144 took the most days to achieve GS31 (136 days).

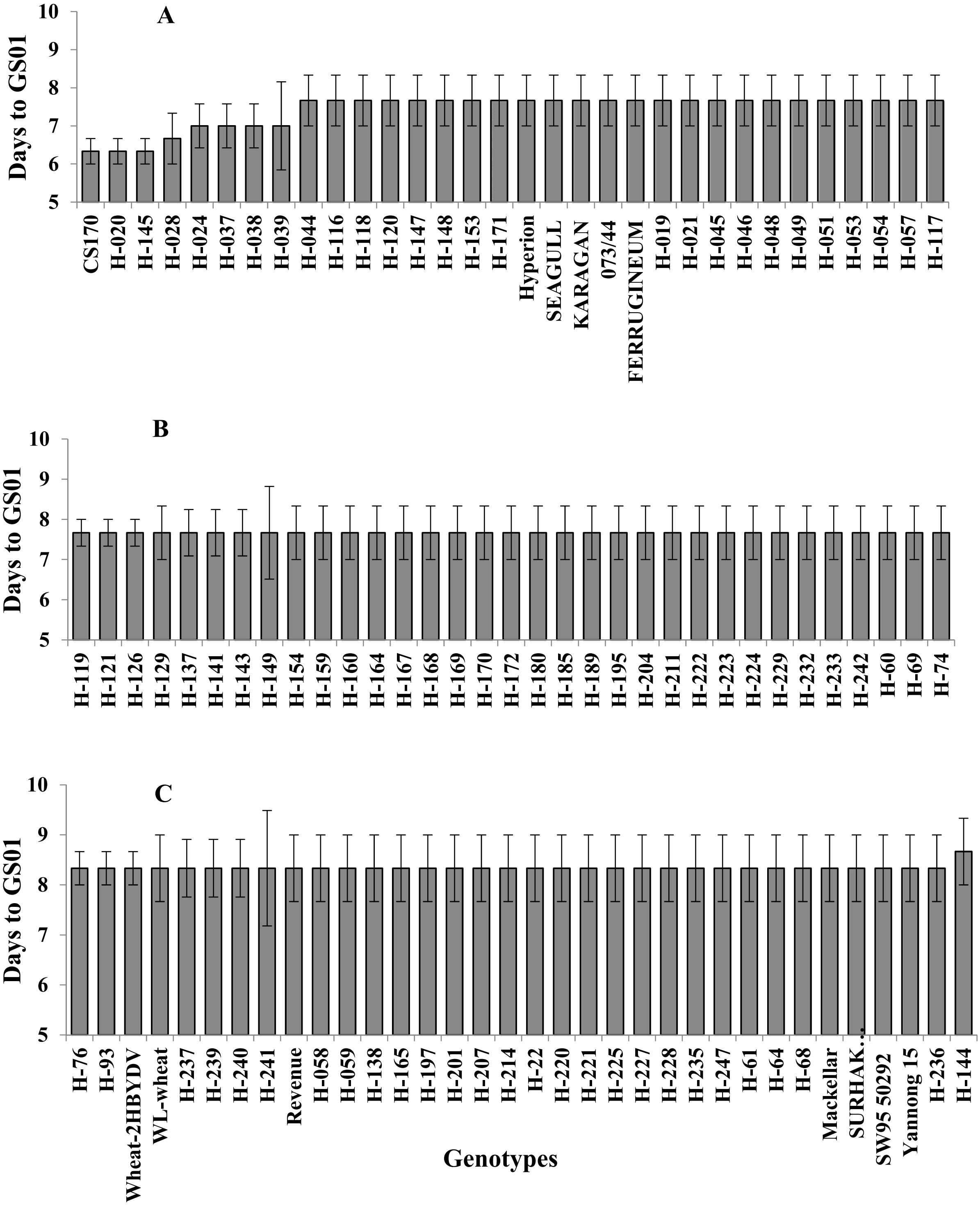


Figure 5.2. Days to GS01 (A, B & C) taken by 99 wheat genotypes in a field experiment at the TIA Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

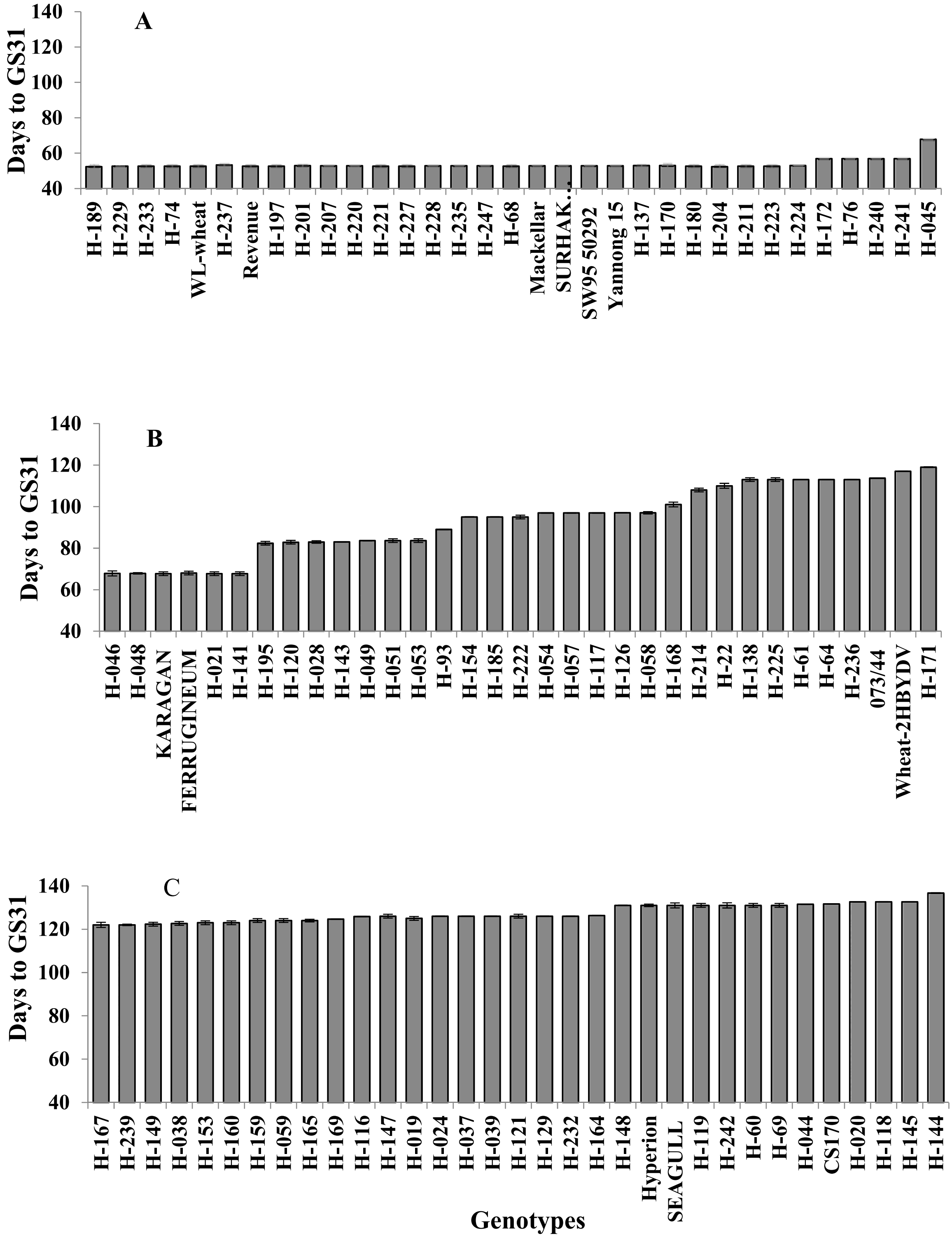


Figure 5.3. Days to GS31 (A, B & C) by 99 wheat genotypes in a field experiment at the TIA Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

5.3.1.1 Days to mid booting stage (GS45)

The days taken by genotypes to reach GS45 (Figure 5.4 and Figure 5.5) showed that there was a significant interaction (P = 0.001) between genotypes and cut treatment. The control treatment varied from 103 days to 183 days. Genotypes with faster development rate were H-247, H-207 and H-228 (control treatments) and H-126, H-220 (cut treatments), whereas genotypes H-159 (control) and H-195 (cut) were the last to reach GS45.

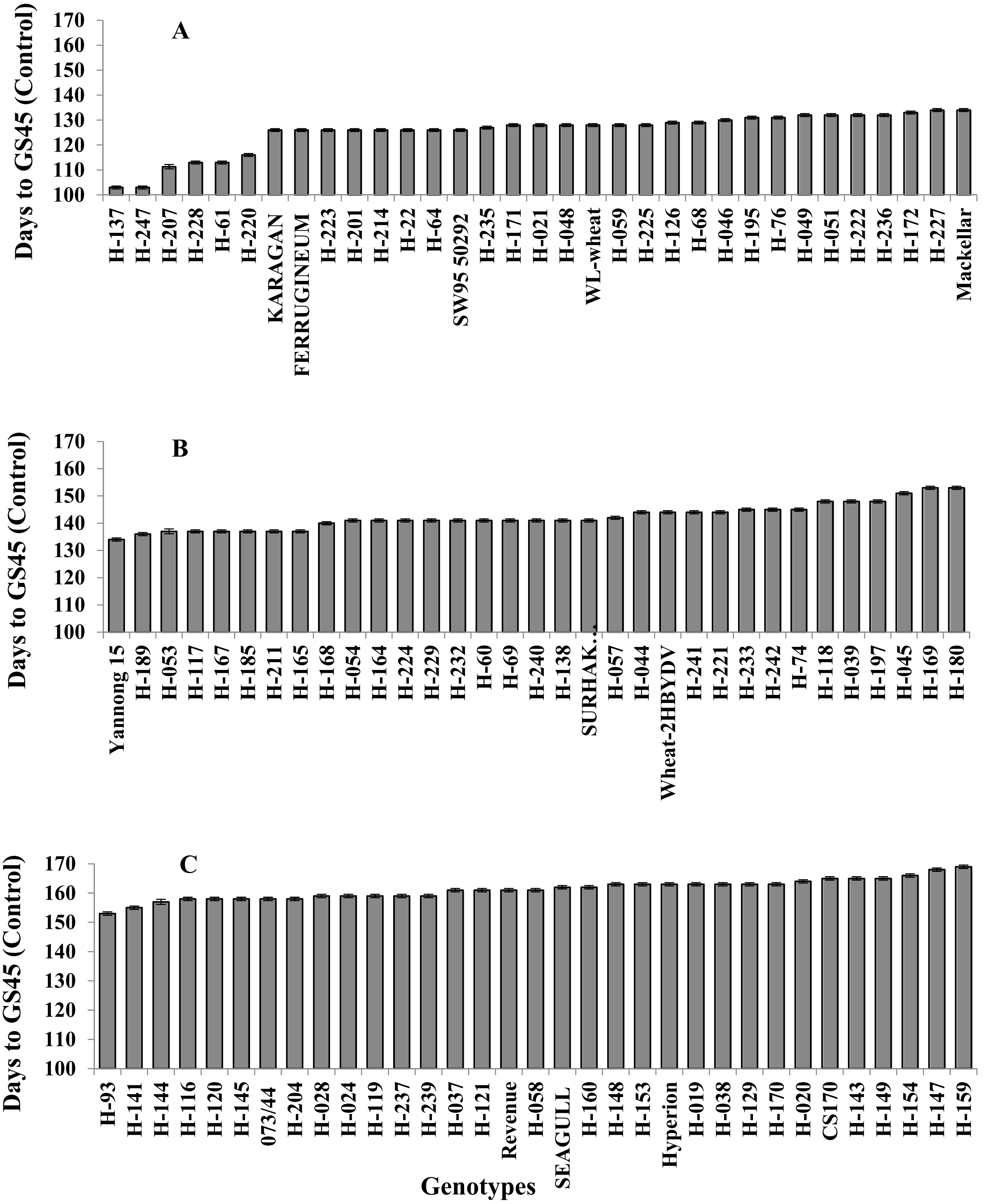


Figure 5.4. Days to GS45 taken by control (A, B &C) plots of 99 wheat genotypes in a field experiment at the TIA Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The interaction between cutting treatment and genotypes was significant at P=0.001. Refer to Figure 5.5 for the cutting treatment. The SE bars represent the SEM.

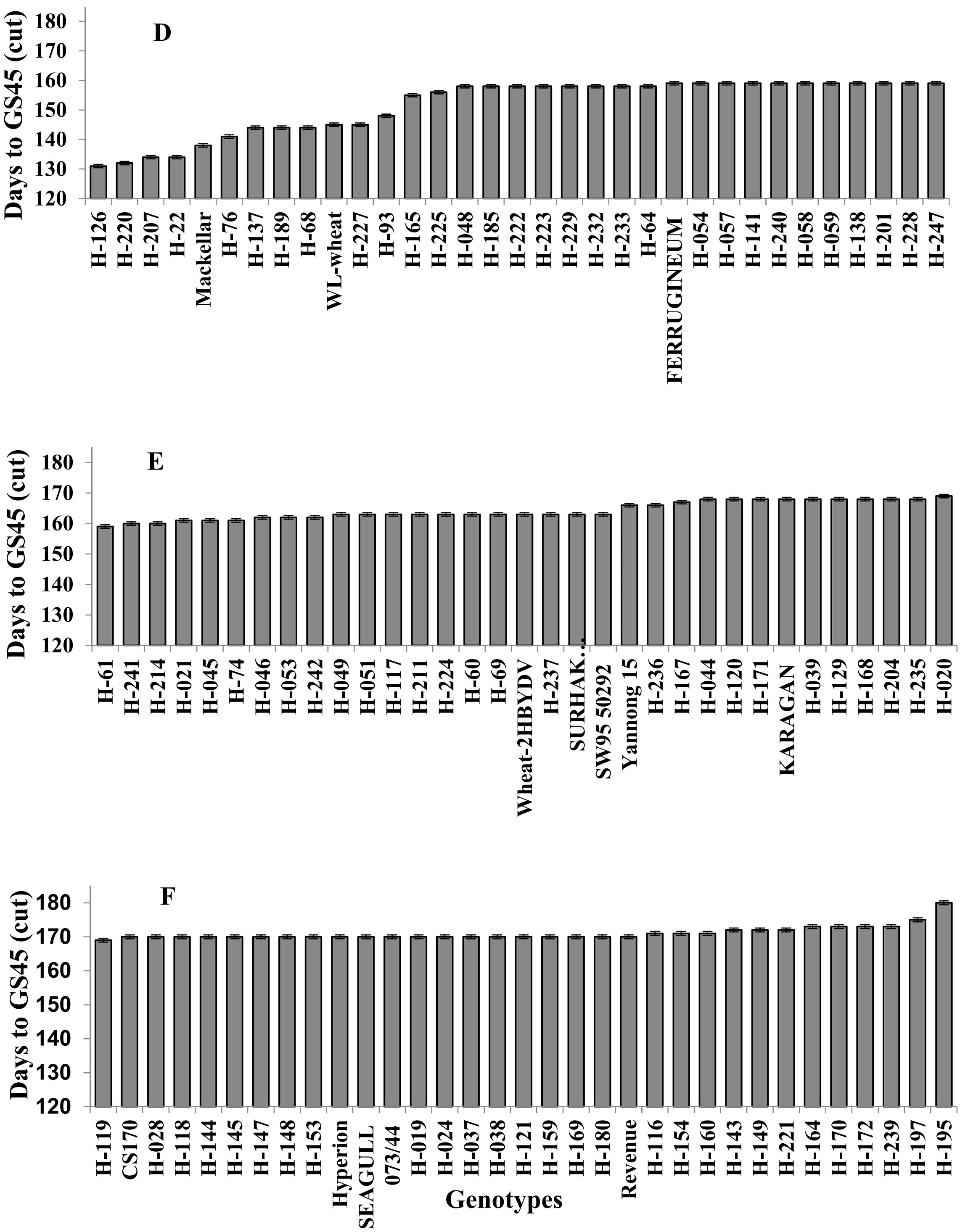


Figure 5.5. Days to GS45 taken by cut treatment (D, E & F) of 99 wheat genotypes in a field experiment at the TIA Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

5.3.2 Morphological traits

5.3.2.1 Plant height at stem elongation (GS31) and mid booting (GS45)

Significant differences were found among wheat genotypes for plant height at GS31 (Figure 5.6), with height ranging between 13.3 and 46.6 cm. The genotype H-051 and H-241 were the tallest, whereas H-120 was the shortest.

There was a significant interaction for height between wheat genotypes and cutting treatment. Due to the number of entries, data is shown in separate figures for control (Figure 5.7) and cut (Figure 5.8) treatments at GS45. The genotype H-201 was the tallest uncut control and genotypes CS170, SEAGULL and H-019 were the shortest. On the other hand, Mackellar was the tallest of the cut treatments, whilst genotypes H-019, H-044 and SEAGULL were the shortest cut treatments. These were all shorter than the cutting height at GS45 of the local check variety, Revenue.

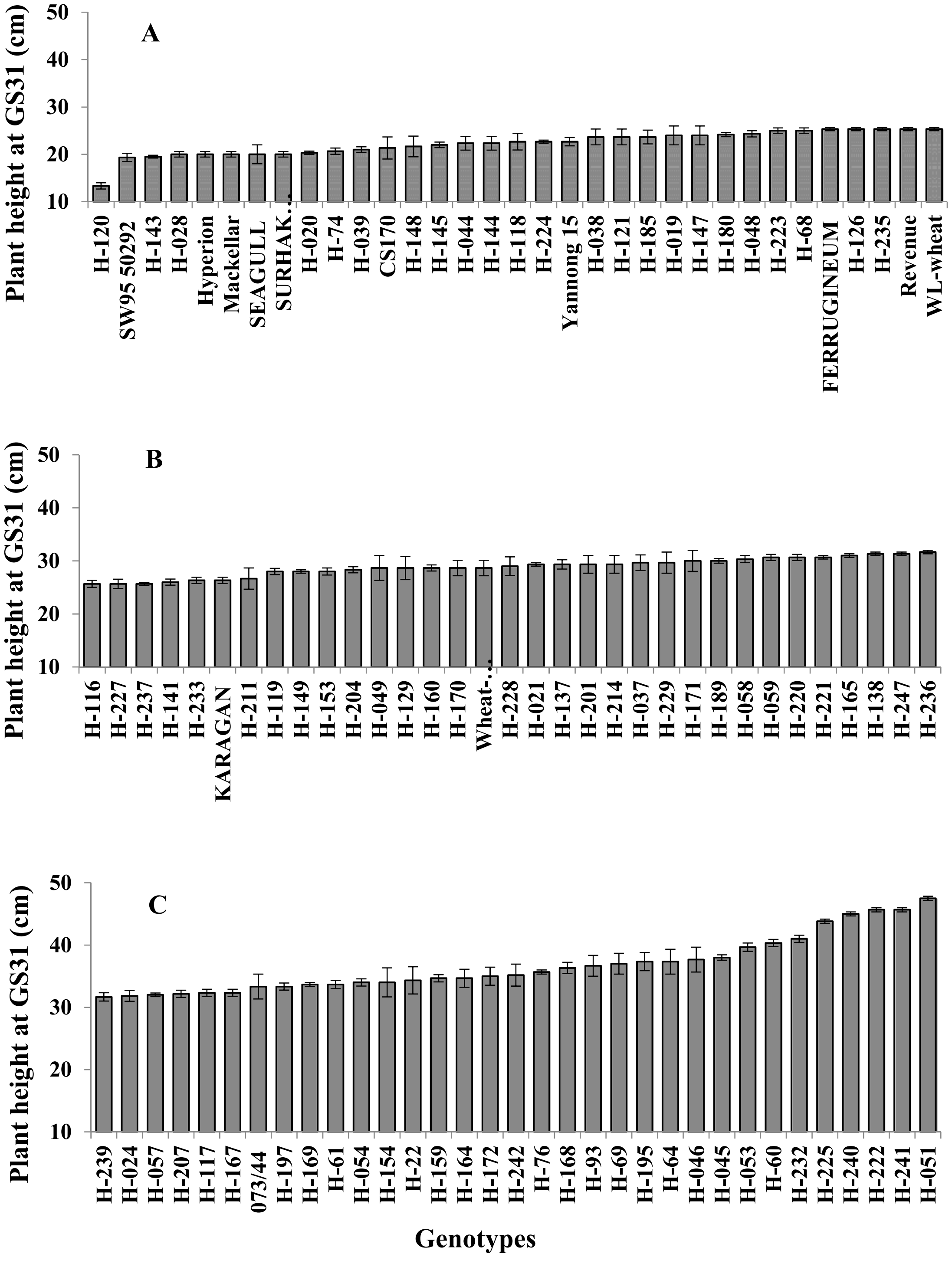


Figure 5.6. Plant height (cm) at GS31 (A, B & C) of 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

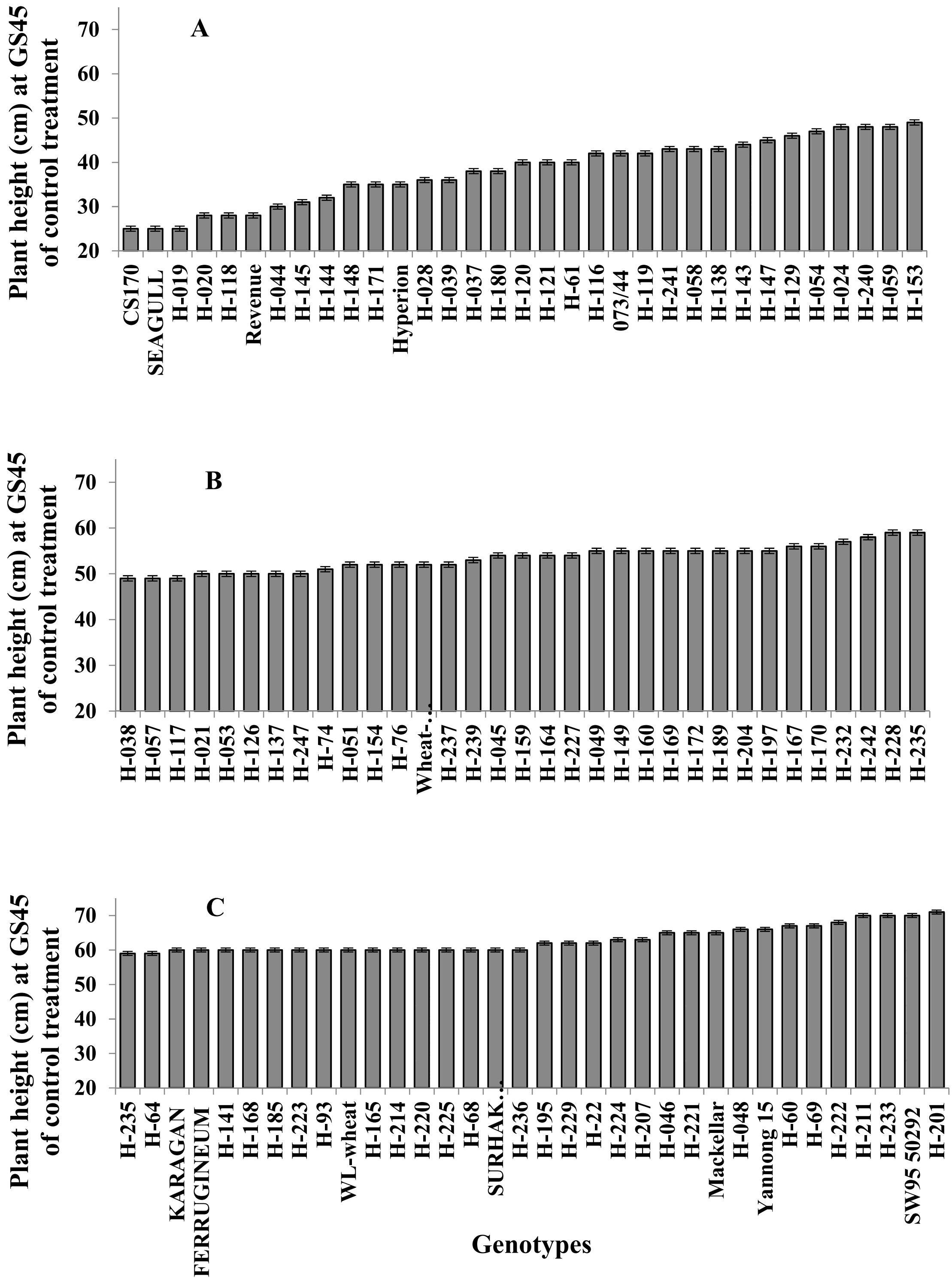


Figure 5.7. Plant height (cm) at GS45 of control (A, B & C) plots of 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

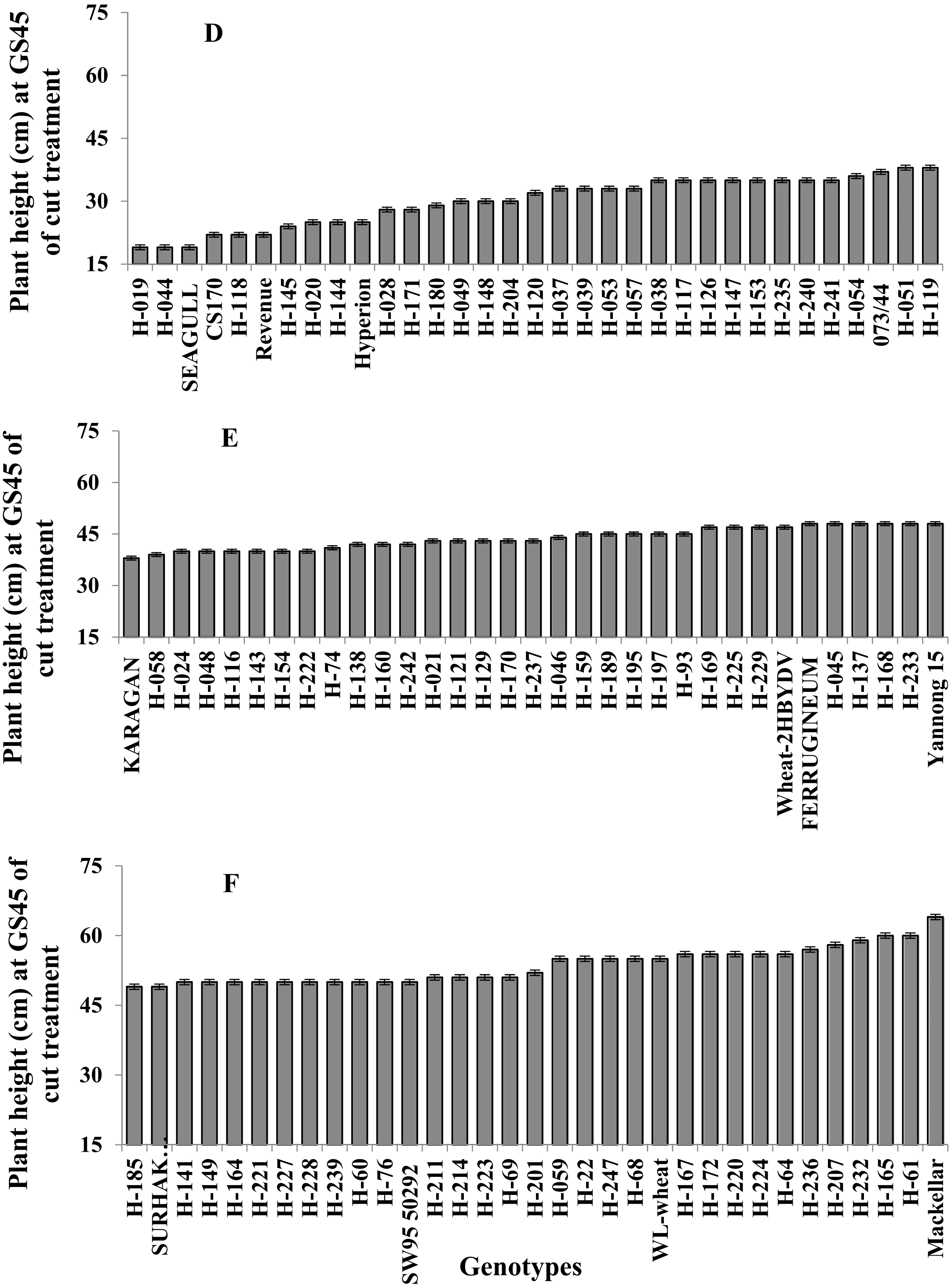


Figure 5.8. Plant height (cm) at GS45 of cut treatment (D, E & F) of 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

5.3.2.2 Number of tillers plant^{-1} at GS31 and Number of leaves main stem^{-1} at GS31

Genotypes varied in number of tillers (Figure 5.9) before forage was cut as GS31, with the number of tillers plant^{-1} ranging between 4 and 15. The maximum number of tillers were recorded for genotype CS-170, H-145, H-020, H159, H-160 and H-044. The genotype FERRUGINEUM had fewest tillers (4). The main effect of cutting treatment and interaction between genotype and cutting treatment for the number of tillers per plant were not significant ($P>0.05$).

Number of leaves on main stem also varied ($P<0.05$) among genotypes (Figure 5.10) and ranged from 3 to 5.3 leaves. Genotypes H-172, 073/44, CS-170, H-020, H-022, H-024, Hyperion, Seagull and wheat-2HBYDV had around 5 leaves number main stem^{-1}. The main effect of cutting treatment and interaction between genotype and cutting treatment for the number of main stem leaves were not significant ($P>0.05$).

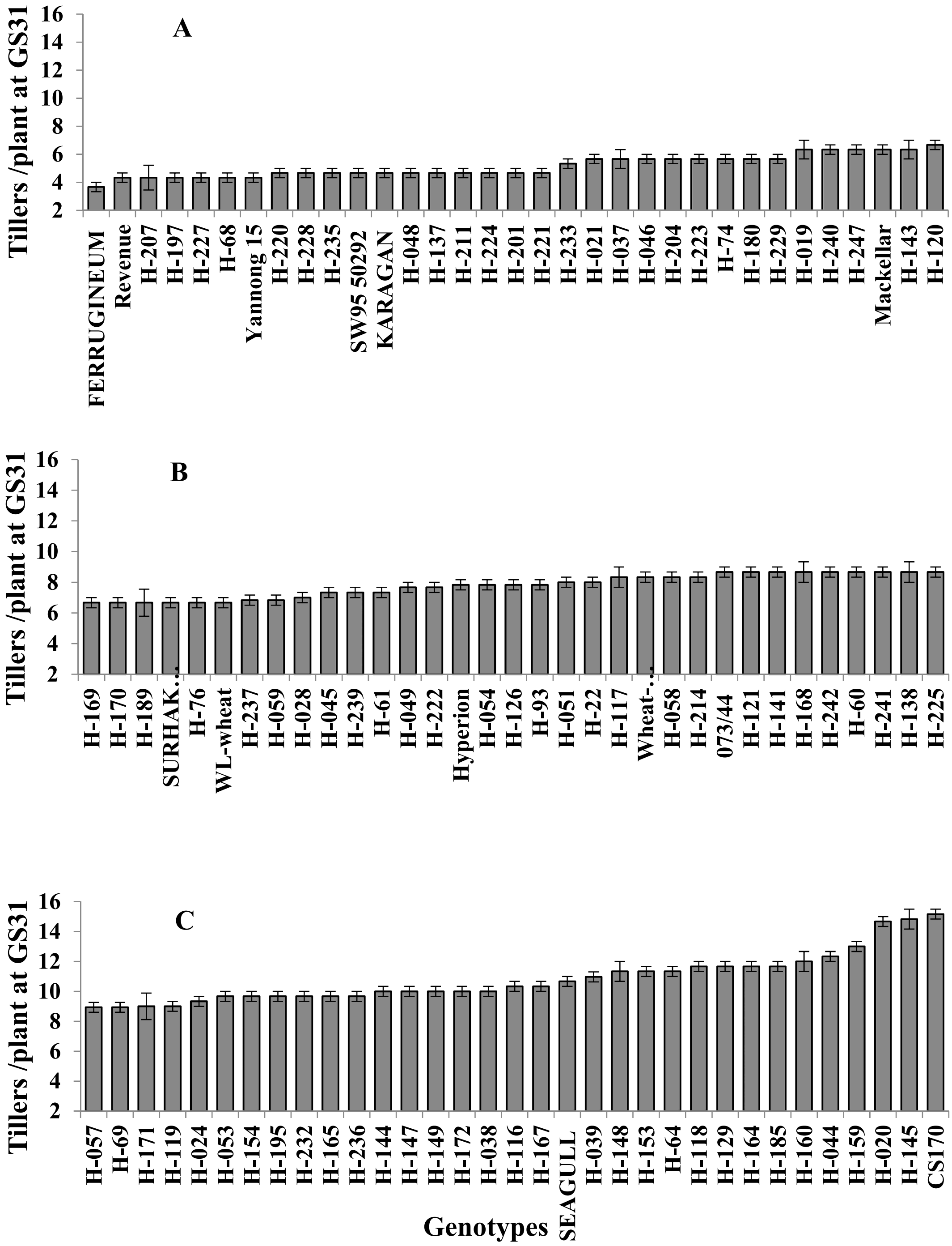


Figure 5.9 Number of tillers per plant (A, B &C) recorded for 99 genotypes recorded at GS30 in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to30 September 2016. The SE bars represent the SEM.

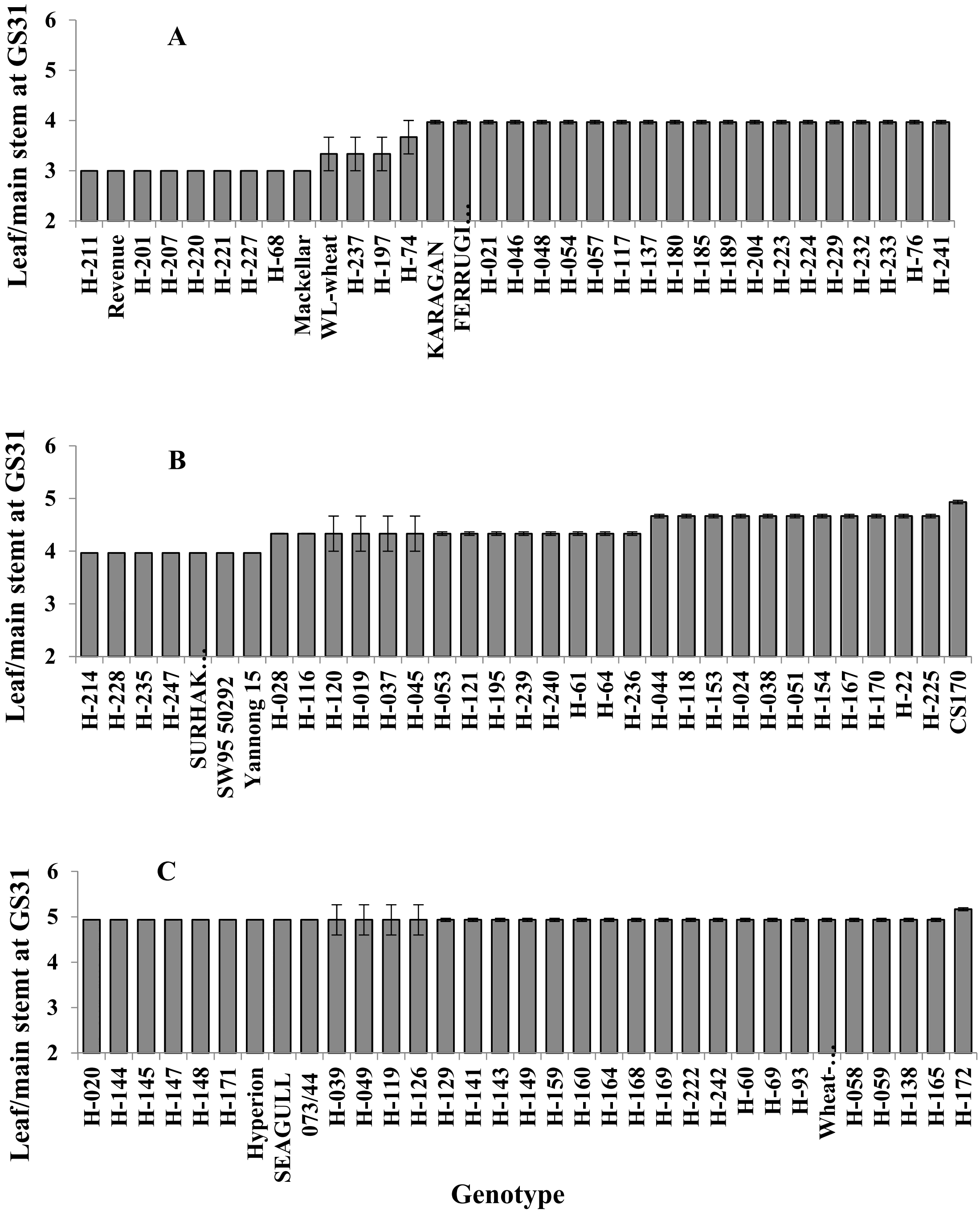


Figure 5.10 Number of leaves per main stem (A, B & C) recorded for 99 genotypes recorded at GS30 in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

5.3.2.3 Forage yield dry matter

Forage yield of all genotypes cut at 5 cm from ground level at GS31 were significantly different (Figure 5.11) and ranged from 0.50 t ha^{-1} to 2.23 t ha^{-1}. The largest forage yield was recorded for genotype H-051 (2.23 t ha^{-1}) with similar yields were recorded for genotypes H-024, H-053 and H-232. The lowest forage yield was recorded for H-019 and H-143 (0.5 t ha^{-1}).

5.3.2.4 Total dry matter yield

Total biomass yield ranged from 0.90 t ha^{-1} to 3.39 t ha^{-1} (Fig. 5.12) at GS31. The highest total biomass yield was produced by genotypes H-051 (3.39 t ha^{-1}), H-024, H-232 and H-053. The lowest yield (0.9 t ha^{-1}) was recorded for genotypes H-019, the only genotype yielding less than 1.0 t ha^{-1}.

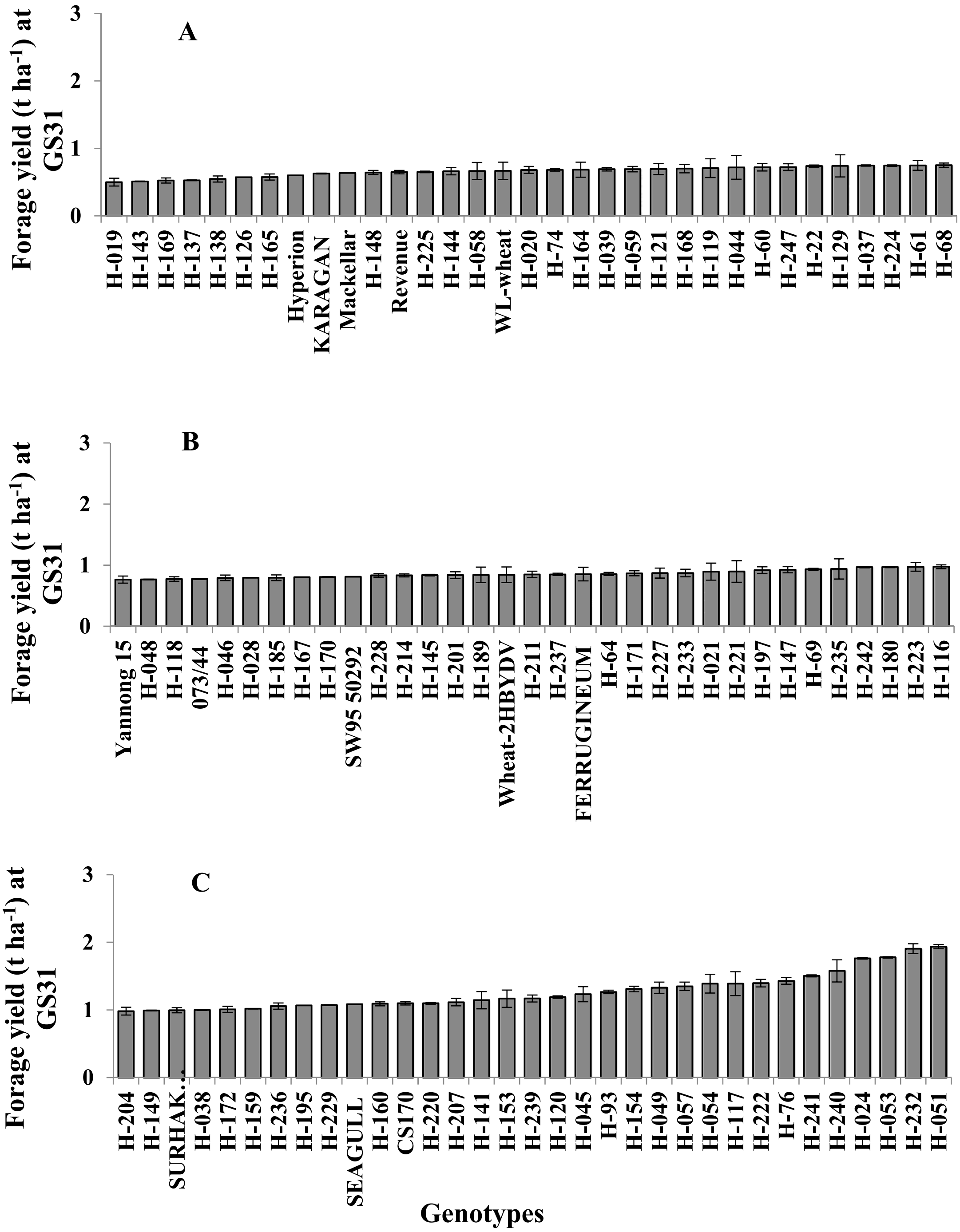


Figure 5.11 Forage yield (t ha^{-1}) (A, B & C) of 99 genotypes recorded at GS30 in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

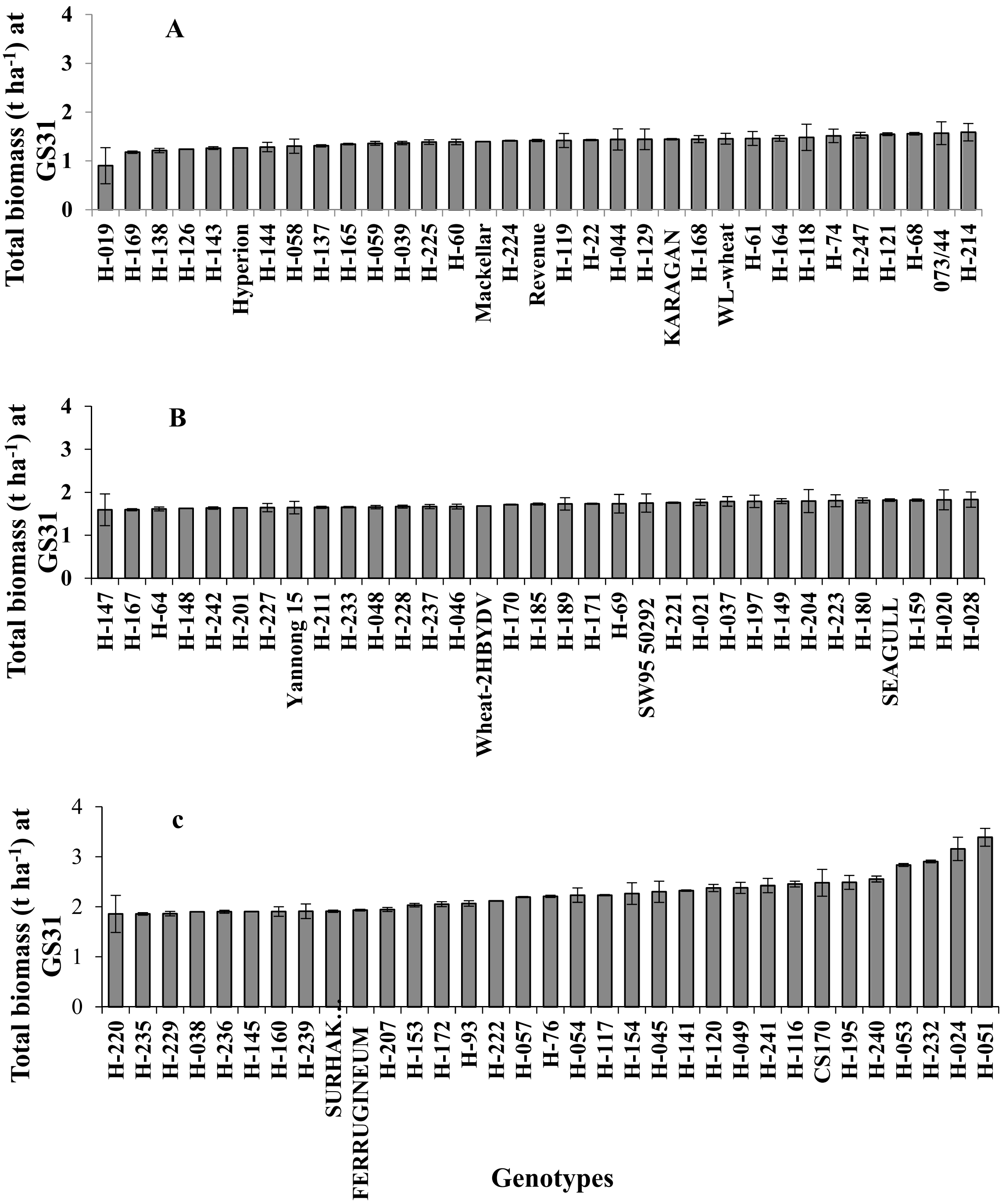


Figure 5.12 Total biomass (t ha^{-1}) of 99 genotypes recorded at GS30 (A, B & C) in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The bars represent the SEM.

5.3.2.5 Growing degree-days (ºCd)

Significant differences were recorded among genotypes for GDD to reach GS21, GS31 and GS45 growth stages (P=0.001). The main effect of cutting treatment and interaction between cutting treatment and genotype for GDD was not significant (P>0.05).

The number of GDD ranged between 126 to 163ºCd for all genotypes to reach to GS01. More GDD to GS01 were recorded for H-144 (163 ºCd), while in comparison other genotypes CS-170, H-020 and H-145 accumulated only 126ºCd to GS01 (Figure 5.13).

GDD from sowing to GS21 ranged from 385 to 511ºCd. The highest GDD were recorded for genotype H-019 (511ºCd). The remaining genotypes, such as H-153, SEAGULL and H-038 had a similar GDD of 396 to 417 ºCd (Figure 5.14).

GDD from sowing to forage cutting at GS31 (Figure 5.15) ranged from 744 to 1478 (ºCd). The highest GDD (1478ºCd) to forage cut were recorded by the genotypes H-144, H-118 and H-145. The lowest thermal time to GS31 were accumulated by genotypes H-137, H-189, H170.

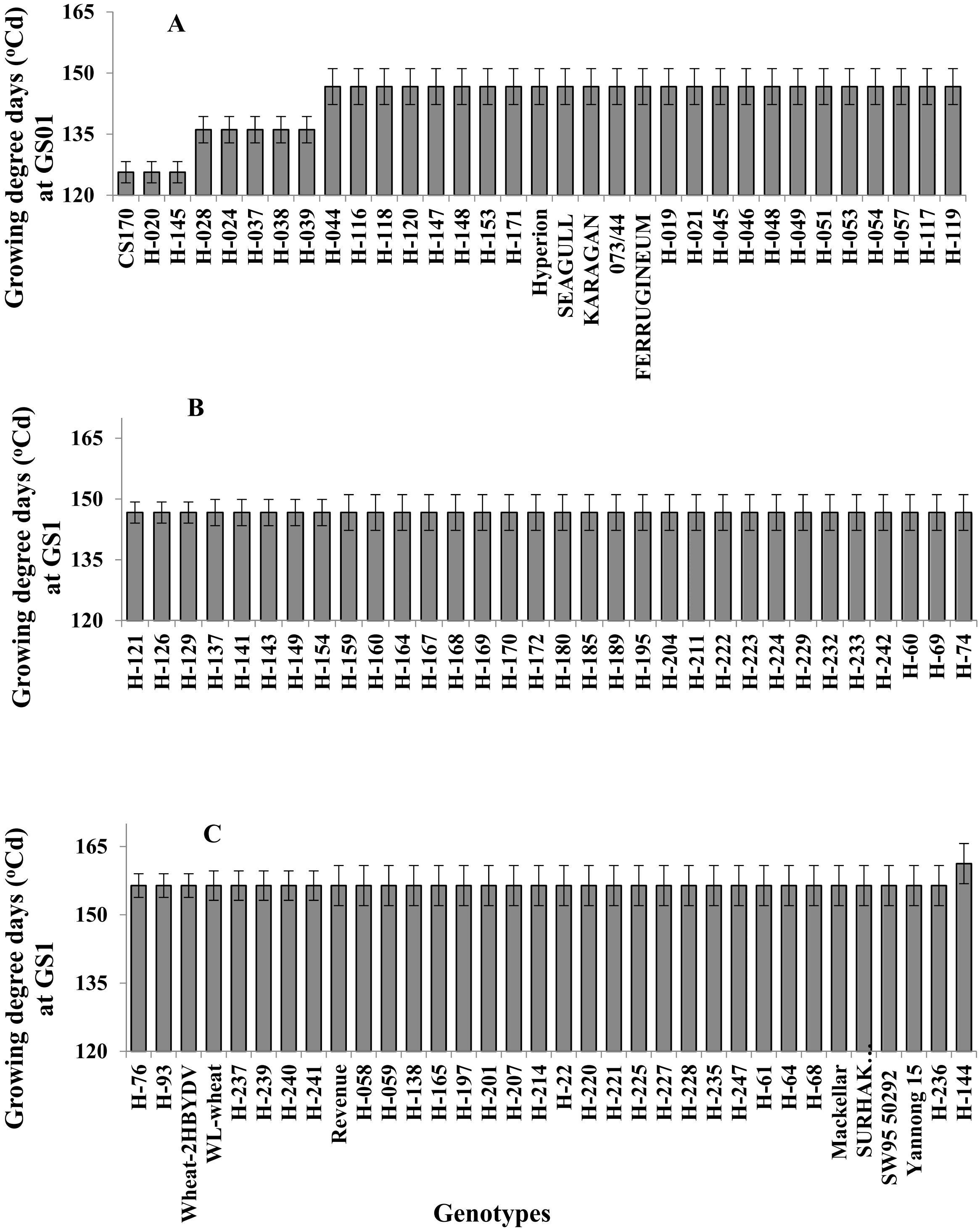


Figure 5.13. Growing degree days (ºCd) from sowing to GS01 (A, B & C) accumulated by 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

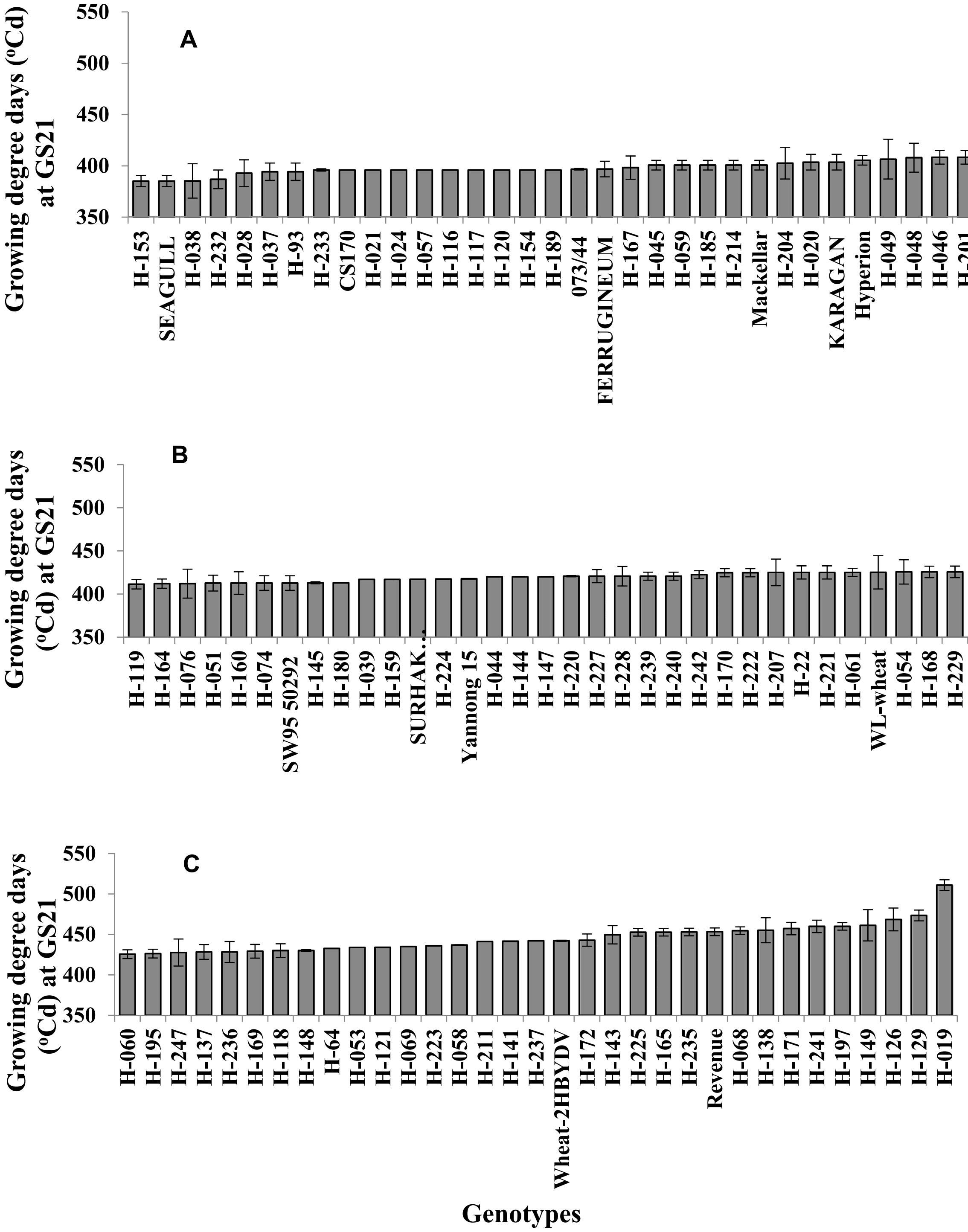


Figure 5.14. Growing degree days (°Cd) from sowing to GS21 (A, B & C) accumulated by 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

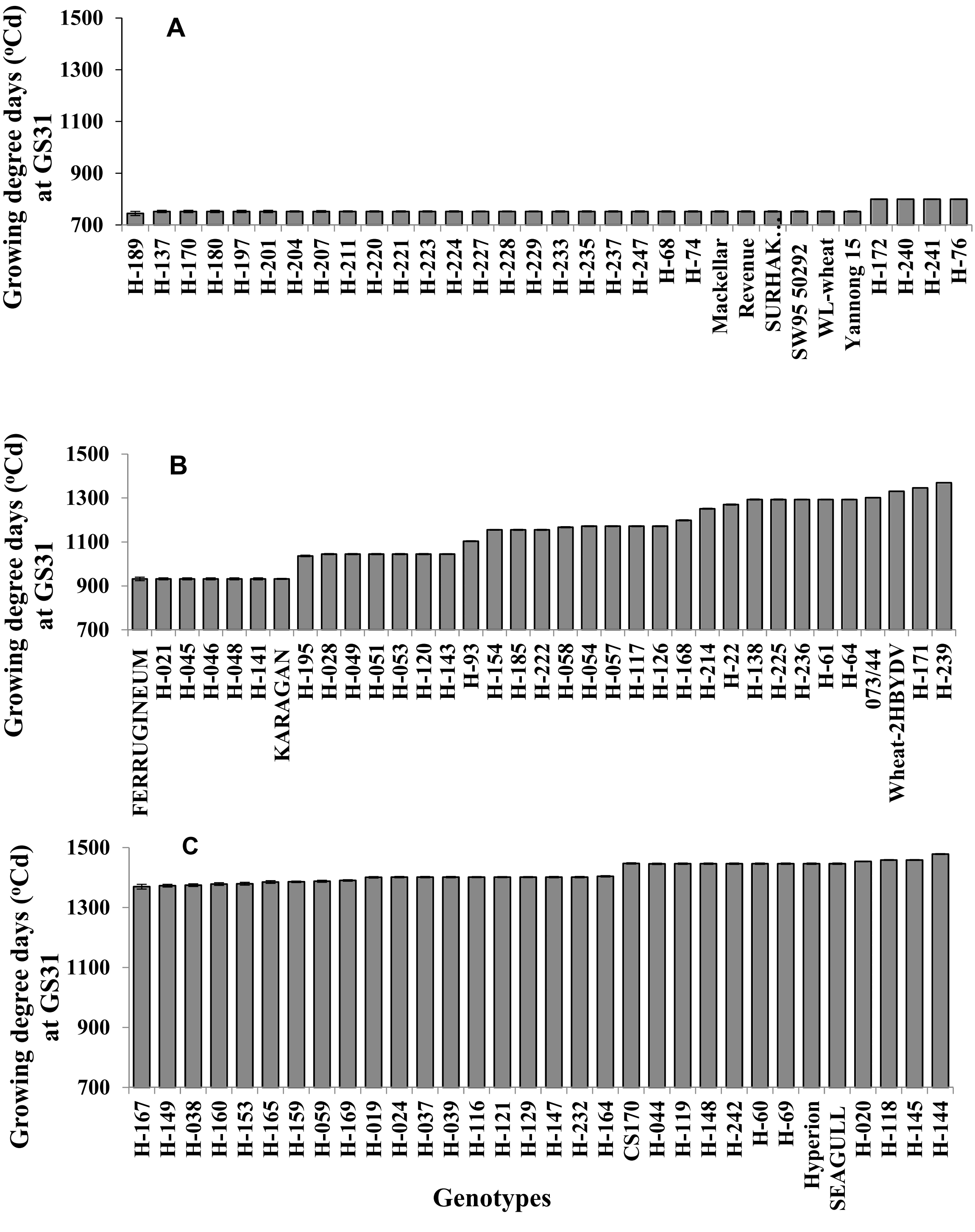


Figure 5.15. Growing degree days (ºCd) from sowing to GS31 (A & B) accumulated by 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

The GDD from sowing to GS45 accumulated had a significant interaction between cutting height and genotype (P=0.001). The control treatment ranged from 1221 to 1719 (ºCd). The highest GDD (1719ºCd) (Figure 5.16) was recorded for genotypes such as H159, H147, Hyperion, Revenue, CS170, and Seagull. The lowest thermal time had a significant interaction between cutting height and genotype (P=0.001). accumulated was (1222ºCd) by genotype H-137.

There was a mean difference of 200 ºCd between the control and cut treatment, e.g. genotypes H-137, H-247 accumulated 1221 ºCd GDD to GS45 in control plots, whereas the same genotypes took 1599 ºCd and 1645 ºCd GDD, respectively, to regrew and achieve GS45 in cut plots. Strong winter types took longer to reached GS31 and recovered earlier. H-195 accumulated the most GDD at 1906 ºCd (Figure 5.17). The genotype H-220 responded rapidly to the defoliation by accumulating GS45 in 1412 ºCd followed by H-207 and H-22. These three genotypes reached mid booting earlier than Mackellar.

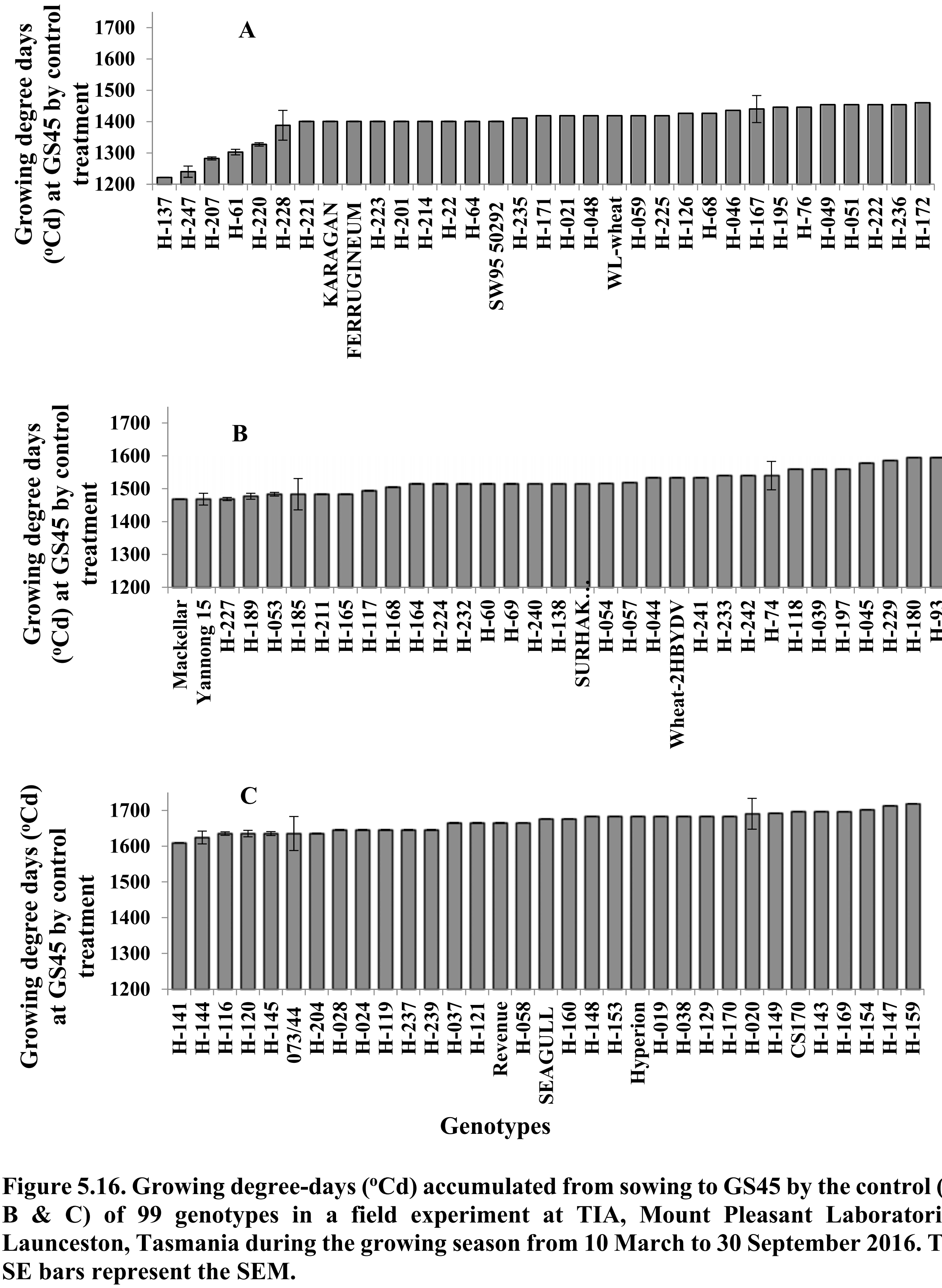
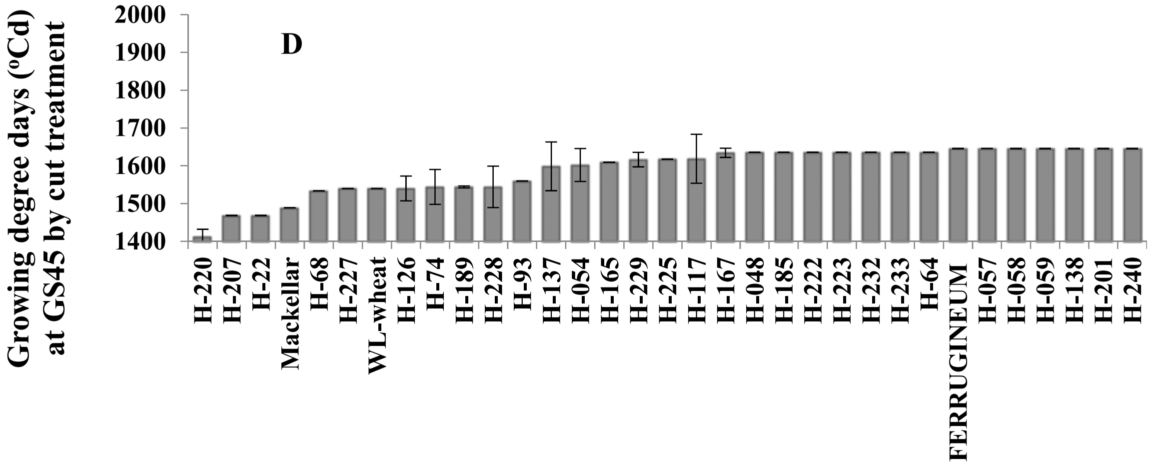
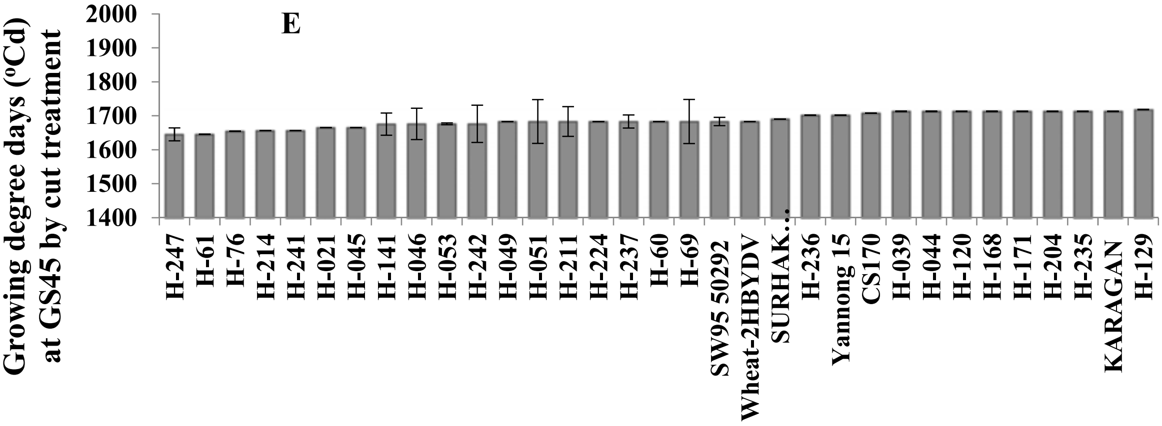


Figure 5.16. Growing degree-days (ºCd) accumulated from sowing to GS45 by the control (A, B & C) of 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.





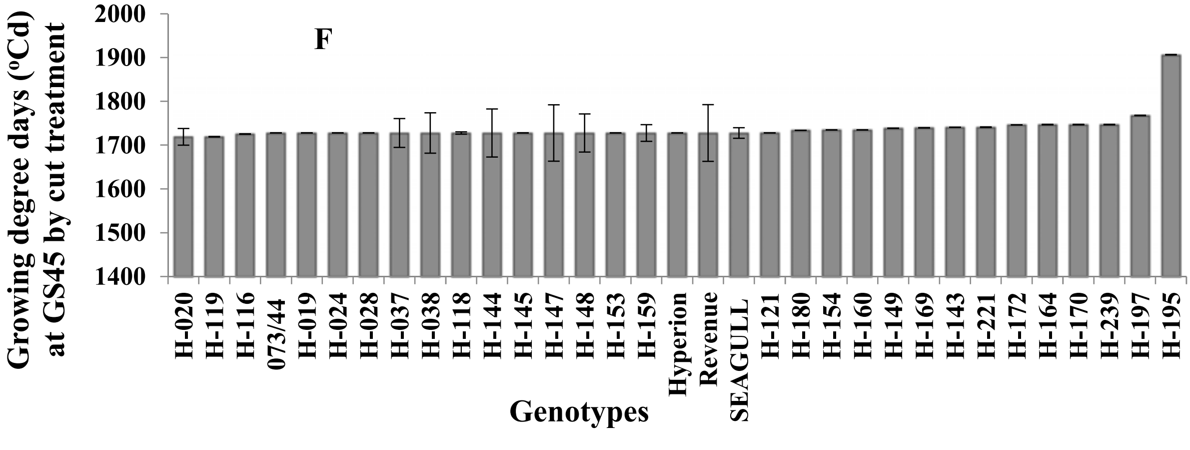
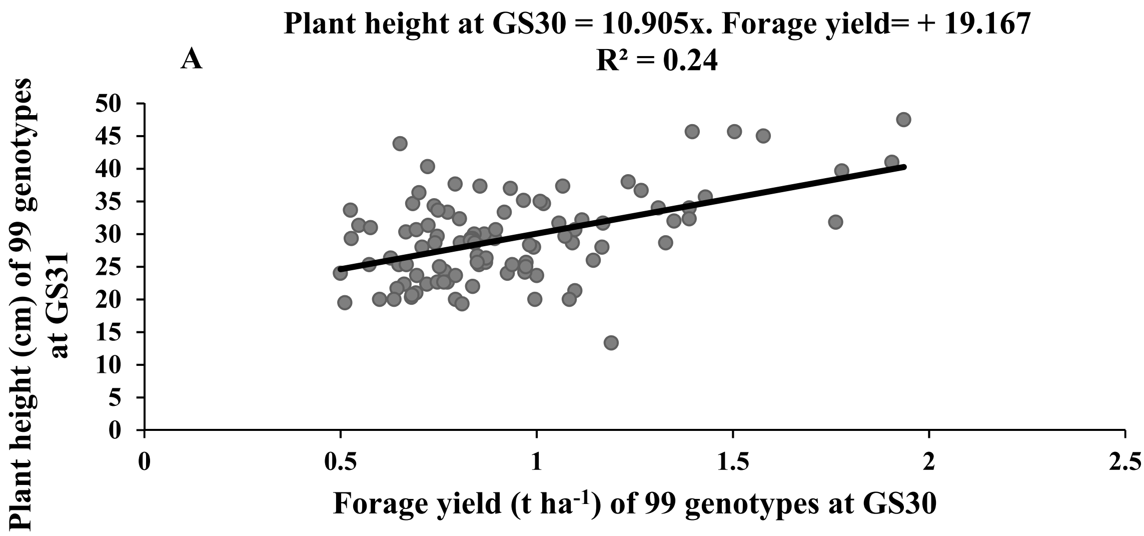


Figure 5.17 The growing degree days (ºCd) accumulated from sowing to GS45 by cut (D, E & F) by 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016. The SE bars represent the SEM.

5.4 Correlations

A significant positive correlation ($R^2 = 0.24$; $P<0.001$) was found between plant height and forage yield of the 99 genotypes at GS31 (Figure 5.18A). Positive correlation ($R^2 = 0.5798$) was found between number of tillers at GS31 and days taken by 99 genotypes to reach GS31 (Figure 5.18B). This indicates that the genotypes having greater number of tillers took maximum number of days to reach GS31.



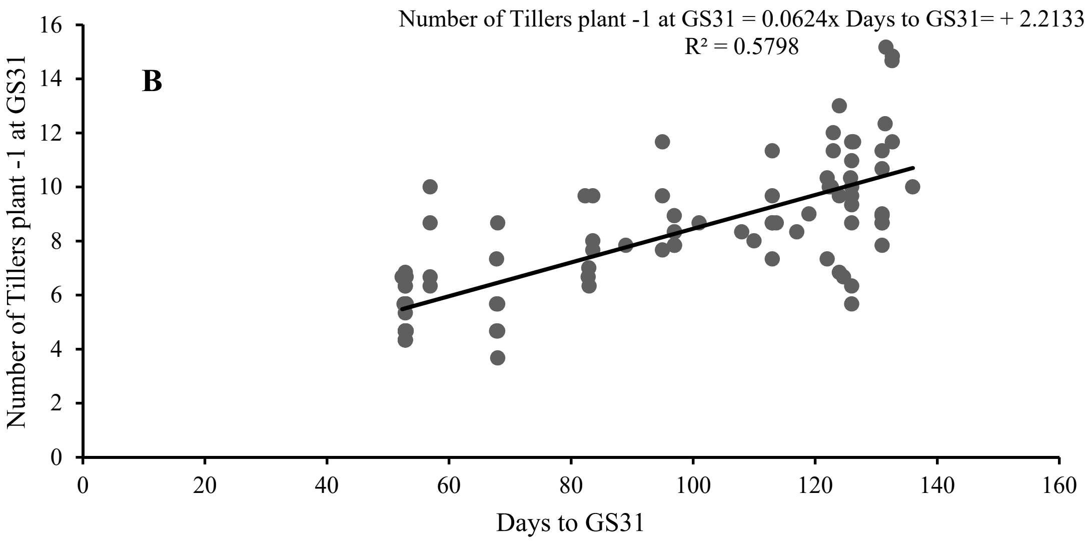


Figure 5.18. (A) Correlation between plant height (cm) at GS31 and forage dry matter yield (t ha^{-1}). (B) Number of tillers plant $^{-1}$ and Days to GS31 of 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016

There was no relationship between days to GS31 or GS45 and biomass yield (Figure 5.19A & B). This indicates that biomass production is independent of the duration of vegetative growth. Further research would be required to take an experiment through to anthesis and maturity to determine if biomass yield was in fact independent of maturity type.

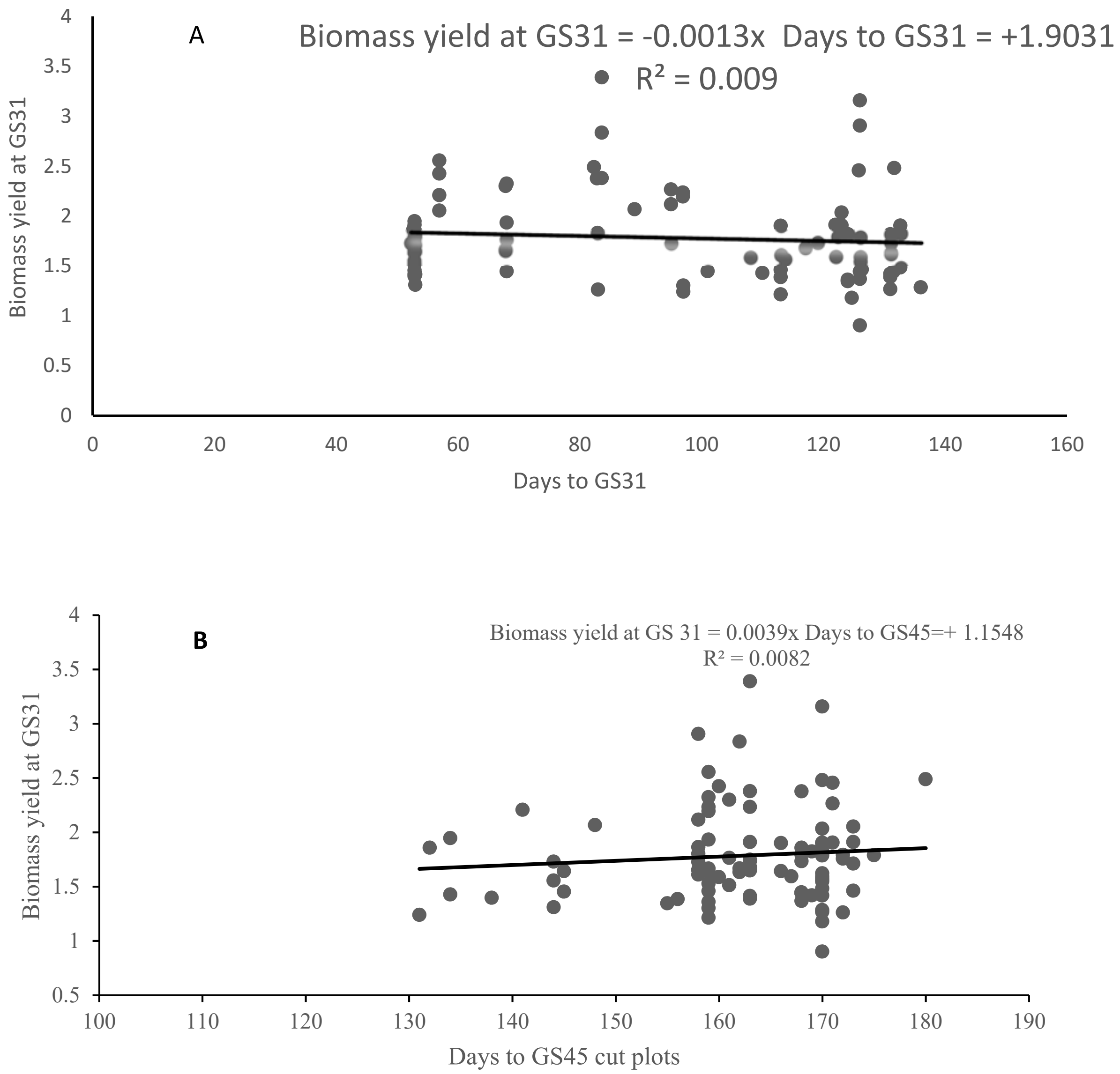


Figure 5.19. (A) Correlation between Biomass yield (t ha^{-1}) at GS31 and Days to GS31 (B) Correlation between Biomass yield (t ha^{-1}) at GS31 and Days to GS45 of cut treatment of 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016

A slight positive correlation ($R^2 = 0.2054$) was found between days to GS45 control plots and days to GS31 taken by 99 genotypes (Figure 5.20). This indicates that the genotypes having strong winter type growth habit took more days to reach GS31 than spring types and same pattern was observed by genotypes at GS45.

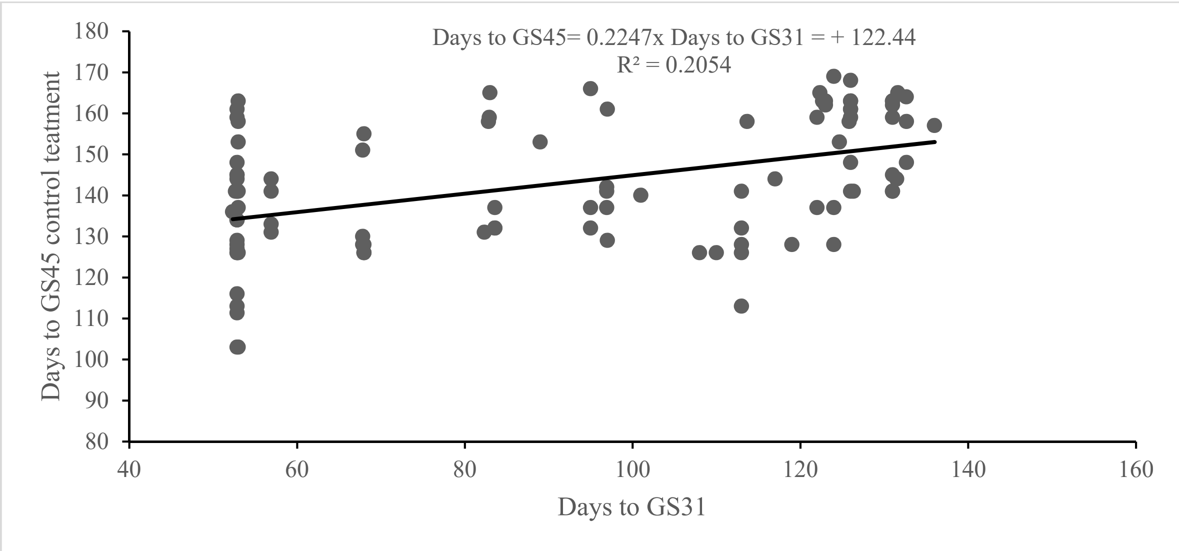


Figure 5.20. Correlation between Days to GS45 of control plots and Days to GS31 of 99 genotypes in a field experiment at TIA, Mount Pleasant Laboratories, Launceston, Tasmania during the growing season from 10 March to 30 September 2016

5.5 Discussion

A wide range of wheat genotypes were sown in early March 2016 to evaluate the impact of cutting on different phenological and morphological traits. The days taken to establishment (GS01) varied among genotypes and ranged from six to eight days. The genotypes CS170 and H-020 emerged significantly earlier (6.3 days) and H-144 achieved maximum 8.8 days to GS01. More than 90 genotypes took seven or more days to reach GS01 and took more than 100ºCd to complete emergence. These results are consistent with McMaster et al. (1992), who observed that wheat requires more than 100ºCd to fully emerge from the ground. GDD from GS01 to GS45 varied among all the genotypes. A minimum of 126ºCd were accumulated by H-020 and H-144 took the highest GDD to GS01 and GS31.

As the genotypes progressed toward GS31, morphological and phenological differences became more visible. Few genotypes started stem elongation (GS31) before two months after sowing whereas some took more than four months. The winter-type genotypes accumulating more GDD reached GS31 later due to their vernalisation requirement. This clearly shows the diversity among the genotypes for maturity type and plant height, where earlier and taller genotypes reached GS31 faster than later-maturing genotypes. For example, H-189 (a tall genotype) took 52 days to reach GS31 with a height of 30 cm, whereas H-144 (a short genotype) took 136 days to reach GS31 and was only 25 cm tall. This may also demonstrate tall genotypes growth rate tends to be faster than intermediate and prostrate genotypes (Redmon et al., 1996), and although the shorter variety had more tillers at GS31 (7-10 for H-189), the taller variety had more biomass at GS31. Further, the correlation between the plant height and GDD showed that the genotypes requiring greater GDD were slightly shorter. Shorter genotypes also tillered more before and after defoliation (Harrison et al., 2011a), and later warmer temperatures helped advance as crop to further.

The number of tillers per plant and leaves per main stem at GS31 varied significantly among genotypes. The most tillers (15.3) were observed for genotype CS170. In contrast, the lowest number of tillers (4) were recorded by genotype Ferrugineum at GS31. Greater tiller number is a highly desired character for DP productivity as it increases the forage yield and contributes in the post cutting growth and recovery by providing more photosynthetic tissue and reserve nutrients (Richards, 1988).

This study showed that cutting significantly affected the regrowth of genotypes. The uncut genotypes in the control plots took from 103 to 183 days to reach booting (GS45). Cutting delayed growth relative to the uncut control and genotypic differences were observed. For example, the genotype H-195 took 108 days to reach GS45 whereas H-126 reached GS45 in 131 days after cutting at GS31. Since all the genotypes were cut at the same height from ground level it can be concluded that differences among the genotypes are associated with their genetic makeup (Tian et al., 2012) but tempered by environmental influences. However, some genotypes like Revenue, Yannong, Mackellar, H-126, H-227, H-237, and H-147, H-165 and H-164 took similar time till GS45 under the control and cut treatment due to rapid regrowth and recovery time indicating lesser influence of environmental stimuli.

The rate of regrowth expressed in terms of calendar time is confounded by differences in temperature and potentially photoperiod (Manupeerapan et al., 1992). However, this may be partially overcome by reporting the regrowth in terms of GDD. For example, genotype H-220 responded quickly to cutting and accumulated the shortest GDD to reach GS45. H-220 required 132 days to GS45 and the process of normal growth and development was delayed as compared with uncut plants. The GDD accumulation of genotypes after defoliation was almost equal as in the control, with a difference in plant height of only 1-10 cm. Hence there is the potential of some genotypes to regrow quickly. The average minimum and maximum temperature during the experiment were 6.5ºC and 16.5ºC respectively. The temperature after GS31 was relatively cooler compared with earlier GSs (Figure 5.1), therefore, the growth rate of defoliated plant was slower than the control as this might have put defoliated plant in stress by disturbing the source sink relationship and N mobilization and affected the growth rate of defoliated plant.

All the genotypes showed significant differences among GDD taken to reach GS31. The genotypes differ in morphological characteristics and genetic origin. Therefore, the difference among them was expected. The accumulation of GDD by the control and cut treatment at GS45 showed a difference of 0-25%.

Dry matter yield at GS31 of among genotypes was significantly different. Genotype H-051 produced the highest forage (2.23 t ha^{-1}) and total biomass (3.39 t ha^{-1}) yield among all genotypes. Similarly, genotypes H-232, H-053. H-24 and H-240 had a relatively high forage and total biomass yield compared to other genotypes included in the study. A positive correlation was observed between plant height and forage yield, suggesting possible selection of potential genotypes for DP system based on height. Height is generally expected to be one of the most useful attributes because tall genotypes tended to have a larger forage yield plus regrowth potential (Redmon et al., 1995) in addition to, disease resistance or drought tolerance.

There was a trend for plants with more main stem leaves to have more tillers and hence better regrowth than genotypes with fewer leaves and tillers. For example, genotypes H-068 had fewer leaves per main stem (3) whereas genotype H-172 had the most (5.3) leaves per main stem among all genotypes at GS31. Therefore, number of leaves and number of tillers contributes to the residual biomass which in turn can influence the growth and regrowth after cutting (Winter and Thompson, 1987). This is linked to the photosynthetic activity of the residual leaf area, which has major role in post defoliation growth and development (Seymour et al., 2015). An interesting result was that there was no apparent relationship between forage production during vegetative growth and duration. Typically, biomass production of early maturing varieties is limited by their short duration compared with late maturing varieties (Siddique et al. 1989). By taking advantage of the genotype x environment x management interaction, novel genotypes with the potential to produce more biomass over a shorter duration of time could provide additional management options in DP wheat in Tasmania. However, further glasshouse and field experiments would be required to evaluate biomass production of the Chinese and Australian wheat genotypes through to anthesis and maturity. Another potential benefit is that fast early growth of leaves conserves soil water in rainfed farming systems (Asseng et al. 2002), which has been shown in some environments to improve grain yield (Botwright et al. 2001). Such results indicate that the genotypes should be assessed for other physiological traits that may confer a yield advantage in other Australian production environments (Richards 2002).

5.6 Conclusion

Wheat genotypes included in this study had diverse backgrounds, with most from China and a few from Australia. The genotypes had large differences in growth type (winter, intermediate and late spring) and habit (tall, intermediate and prostrate).

All genotypes emerged and initiated tillering at same time, but there were differences among genotypes in reaching GS31 and GS45. The late spring and intermediate types attained GS31 earlier than winter types. Genotypes including H-51, H-222 and H-241 were taller compared with the other genotypes, which contributed to greater biomass at GS31 and forage yield compared with short statured genotypes.

Time taken by each genotype to reach GS45 (in term of calendar days and GDD) was different. In control plots the winter type genotypes H-137 and H-247 (intermediate and erect respectively) reached GS45 earlier among all genotypes. Genotypes H-220, H-207 and Mackellar reached GS45 earlier accumulating less GDD than other genotypes. The height of some genotypes like H-64, H-165 and H-220 was not affected by defoliation as they achieved almost similar height in control and cut plots when compared at GS45. Genotypes reaching GS31 earlier produced less biomass yield. Similarly, genotypes having greater number of leaves and tiller had higher regrowth potential. This means that these genotypes have an ability to restore the morphological structure that encourages vegetative growth when defoliated before stem elongation stage. Genotypes with good potential regrowth may be included in a breeding program that aims to develop new DP genotypes.

Chapter 6. General Discussion

6.1 Introduction

Among cereal crops wheat is a major crop in Australia so the adoption of wheat for DP productivity is practical option. The major areas focused in selecting DP wheat from existing grain-only varieties are physiology, phenology and morphology depending on agroclimatic zone. This study was designed to evaluate new varieties and defoliation strategies to improve the productivity of DP wheat in Tasmania.

6.2 Overview of thesis

The finding from this research may aid to identify new genotypes for Tasmania that have the potential to be adopted as DP crop based on winter feed and regrowth potential. This study was designed to screen many genotypes to evaluate their DP potential. The genotypes selected were mostly winter types with diversity of growth habit and other attributes having origin from China and Australia.

In Chapter 3, four commonly grown wheat varieties (Revenue, Bolac, Chara and CS170) with different growth habits were grown in a glasshouse to evaluate several cutting strategies. The literature review revealed that defoliation practice according to morphology had not received much research attention. Plants were cut at different heights with respect to plant morphology to measure the response of each genotype to defoliation. It was concluded that all genotypes have potential to regrow if not defoliated below a critical point (ligule / leaf sheath end). During tillering stages, the vegetative growth was rapid relative to reproductive development. The upper (leaves) and lower (sheath) parts were equally contributing to total plant growth and development. Therefore, defoliation should leave a sufficient amount of residual photosynthetic tissue to enable plants to regrow. We concluded that regardless of growth habit, wheat has the potential to regrow after defoliation if it is not cut below leaf sheath zone before GS31.

In Chapter 4 plants were cut according to height from ground to simulate defoliation strategies in the field. The objective of this experiment was to correlate the finding in Chapter 3 with a pragmatic approach that could be applied to many genotypes grown in the field with a uniform cutting height in cm from ground level. Plants of three varieties Bolac, Revenue and CS170 were cut at 5 levels (0, 3, 5, 8 and 10 cm) under two major treatment levels. (Clipping and Crash). Clipping referred to the defoliation from plant tip to 5 cm from ground level, whereas, Crash cutting referred to cutting from ground level to 5 cm above ground.

The results demonstrated that wheat plants cut near ground level (Crash) tend to yield more forage than those that are only Clipped. However, when cut below 5 cm, the plant's capacity for regrowth is significantly reduced.

Overall, cutting the plant at the end of the leaf sheath (Chapter 3) or at 5 cm cutting height (Chapter 4) conserved sufficient length of leaf sheath to enable leaf regrowth and the reproductive meristem growth was not affected. Thus, a cut at 5cm resulted in a reliable estimate of forage yield without risking subsequent recovery or regrowth and was suitably practical to be applied under field conditions. Based on these results the 5 cm cutting height was followed as protocol for defoliation of 99 genotypes of wheat from China and Australia.

In the following experiment (Chapter 5) all genotypes were sown in early March as per best management practice for winter wheat for DP productivity. Genotypes were defoliated at GS31 and post defoliation regrowth was measured to GS45. The genotypes were evaluated by observing days and GDD to attain GS01, GS20, GS31, GS45, and at each GS, height, number of tiller and leaves, forage and biomass were measured. The main conclusions were made according to genotype performance via forage yield and time taken to reach GS45.

6.3 Major findings

Higher forage yield is the primary objective for selecting a wheat variety for DP. The 99 genotypes selected (evaluated in chapter 5) had differences in growth habit and type, this study recorded further traits, phenological and morphological characteristics. Moreover, the phenology and morphology of the genotypes was assessed in both uncut control and defoliated regimes in the Tasmanian environment. The genotypes having higher number of leaves, tillers and days taken to reach stem elongation stage were more likely to produce higher forage yield. There was some indication that biomass production during vegetative growth was independent of maturity type, although this would need to be confirmed in an experiment that continued through to anthesis and maturity. The genotypes accumulating fewer GDD to GS45 were at the risk of frost damage but also had sufficient time to complete latter GSs and expected to produce grain yield. Moreover, some genotypes showed rapid regrowth and had plant height similar to the control plots. Table 6.1 summarises the most preferable genotypes for research moving forwards.

Table 6.1. Potential genotypes identified on the basis of calendar days from sowing to GS31, plant height (cm) at GS31 and GS45, number of tillers and leaves stem^{-1}, forage yield and GDD (ºCd) at Mount Pleasant Laboratories, Launceston, Tasmania during growing season from 10 March to 30 September 2017.

Potential genotypes	H-61, H-165, H-232, H-207, H-236, H-64, H-220, H-224, H-172, H-68, H-22, H-177, H-222, H-93, H-117, H-53, H-76
Defoliation GS/height	Cut at GS 30 / 5 cm
Sowing time	Early March
Calendar days	Requires 100 to 140 days to reach GS31
GDD (ºCd)	These genotypes reached GS45 earlier than rest accumulating 1400 to 1650 (ºCd) GDD, the rest took more GDD ranging from 1650 to 1906 (ºCd)
Plant height (cm)	The height ranged between 25 to 45 at GS31 and ranged between 45 to 65 at Gs45
Number of tillers and leaves/main stem	Number of tillers ranged from 4-10 and number of leaves ranged from 3-5.
Forage yield (dry matter t ha^{-1})	Ranged between 1 to 2.2 (t ha^{-1})

6.4 Shortcoming / gaps

The research was conducted as major part of a Master's degree. The experiments designed in Chapter 3 and 4 were to study defoliation strategies until GS31 to draw a reasonable conclusion before the onset of sowing season for the main trial.

The main trial in Chapter 5 was designed in the field and we did not have the required time and resources to measure leaf greenness, leaf area and physiology of all 99 genotypes The experiment was concluded at GS45 as the sheep from adjacent paddock broken in to and thus we were unable to collect grain yield data.

6.5 Recommendations for future studies

The study evaluated a range of wheat genotypes from China and Australia for their DP potential in Tasmanian growing conditions. This study has demonstrated that if these genotypes are sown in early March, under Tasmanian cool temperate winter conditions, defoliating at 5 cm should be the lowest level wheat crops are cut not later than when crop reaches GS31 (stem elongation). This is because forage dry matter at 5 cm yielded up to 2 t ha^{-1} and was followed by rapid regrowth in terms of height (although these crops were not subjected to water or nitrogen limitation). Although the experiment was terminated at GS45 due to sheep intervention, yet there was sufficient information at GS45 to make some estimation on DP potential. The genotypes listed in Table 6.1 need further evaluation for grain yield potential to estimate the trade-off between forage yield, regrowth and defoliation at different GS and sowing times.

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Chapter 8. Annex.1. Germplasm number, origin, Chinese local name, English name, growth habit and growth type of 99 wheat genotypes grown at Mount Pleasant Laboratories, Tasmania, during the growing season 10 March to 30 September 2016.

No	Genotype	Germplasm number	Origin	local name	English name	Growth habit	Growth type	category
1	**073/44**					winter	I	landrace
2	**CS170**		Australia			winter	P	landrace
3	**FERRUGINEUM**					winter	I	landrace
4	**H-019**	ZM020735	China	红金麦	**Hongjin Wheat**	Strongly winter	I	landrace
5	**H-020**	ZM005012	China	白齐麦	Baiqi Wheat	Strongly winter	P	landrace
6	**H-021**	ZM004454	China	小口红	Xiaokouhong	Semi winter	I	landrace
7	**H-022**	ZM005017	China	兰花麦	Lanhua Wheat	winter	E	landrace
8	**H-024**	ZM000474	China	涿鹿冬麦	Zhulu Winter wheat	winter	I	landrace
9	**H-028**	ZM004412	China	磐石无芒	Panshi (awnless)	winter	P	landrace
10	**H-037**	ZM008963	China	北京8号	Beijing Number 8	winter	I	commercial
11	**H-038**	ZM013548	China	原冬822	Yuandong 822	winter	I	commercial
12	**H-039**	ZM014050	China	吕旱328	Lvhan 328	winter	I	commercial
13	**H-044**	ZM009379	China	铭贤169	Mingxian 169	winter	P	commercial
14	**H-045**	ZM009038	China	东方红23号	Dongfanghong Number 23	winter	I	commercial
15	**H-046**	ZM003498	China	线麦	Xian Wheat	Semi winter	I	landrace
16	**H-048**	ZM011345	China	红花早	Honghuazao	Semi winter	I	landrace
17	**H-049**	ZM005871	China	江东门	Jiangdongmen	Semi winter	I	landrace
18	**H-051**	ZM011446	China	崇阳红麦1	Chongyanghong Wheat 1	Semi winter	I	commercial
19	**H-053**	ZM005540	China	六柱头	Liuzhutou	winter	I	landrace
20	**H-054**	ZM006465	China	蝉不吱	Chanbuzhi	Semi winter	I	landrace
21	**H-057**	ZM010980	China	黄水白	Huangshuibai	Semi winter	I	landrace

No	Genotype	Germplasm number	Origin	local name	English name	Growth habit	Growth type	category
22	**H-058**	ZM007246	China	白蒲(落 青)	Baipu(luo qing)	Semi winter	E	landrace
23	**H-059**	ZM007209	China	早小麦	early wheat	Semi winter	E	landrace
24	**H-060**	ZM007052	China	兰溪早小麦	Lanxi early wheat	Spring	I	landrace
25	**H-061**	ZM005740	China	望水白	Wangshuibai	Semi winter	E	landrace
26	**H-064**	ZM007486	China	和尚麦	Heshang Wheat	Spring	E	landrace
27	**H-068**	ZM007298	China	泡子麦	Paozi Wheat	Semi winter	E	landrace
28	**H-069**	ZM010184	China	华东6号	Huadong N6	Semi winter	I	landrace
29	**H-074**	ZM010314	China	鄂麦6号	Emai Number 6	Semi winter	I	commercial
30	**H-076**	H01219	China	浙麦1号	Zhemai N 1	winter	I	commercial
31	**H-093**	MY002776	China	St 2422/464(郑引4号	St 2422/464Zhengyin N4）	winter	I	commercial
39	**H-129**	ZM009597	China	西农6028	Xinong 6028	winter	I	commercial
40	**H-137**	ZM017231	China	陕农7859	Shannong 7859	winter	I	commercial
41	**H-138**	ZM009603	China	矮丰3号	Aifeng Number 3	winter	E	commercial
42	**H-141**	ZM022727	China	莱州953	Laizhou 953	winter	I	commercial
43	**H-143**	ZM000215	China	白芒麦	Baimang Wheat	Semi winter	I	landrace
44	**H-144**	ZM003050	China	黄瓜先	Huangguaxian	Semi winter	P	landrace
45	**H-145**	ZM002569	China	半截芒	Banjianmang	Semi winter	P	landrace
46	**H-147**	ZM001674	China	蝼蛄腚	Louguding	winter	P	landrace
47	**H-148**	ZM001846	China	西山扁穗	Xishanbiansui	Semi winter	P	landrace
48	**H-149**	ZM002681	China	红狗豆	Honggoudou	Semi winter	I	landrace
49	**H-153**	ZM002668	China	蚰子麦	Youzi Wheat	winter	P	landrace
50	**H-154**	ZM002974	China	平原50	Pingyuan 50	Semi winter	I	commercial
51	**H-159**	ZM011007	China	阜阳红	Fuyanghong	Semi winter	I	landrace

No	Genotype	Germplasm number	Origin	local name	English name	Growth habit	Growth type	category
52	**H-160**	ZM003807	China	蚂蚱麦	Mazha Wheat	winter	I	landrace
53	**H-164**	ZM011120	China	三月黄	Sanyuehuang	winter	I	landrace
54	**H-165**	ZM002686	China	小佛手	Xiaofoshou	winter	E	landrace
55	**H-167**	ZM003131	China	大口麦	Dakou Wheat	Semi winter	I	landrace
56	**H-168**	ZM004154	China	秃芒麦	Tumang Wheat	Semi winter	I	landrace
57	**H-169**	ZM003069	China	白条鱼	Baitiaoyu	Semi winter	I	landrace
58	**H-170**	ZM003650	China	白芒麦	Baimang Wheat	winter	I	landrace
59	**H-171**	ZM006348	China	大玉花	Dayuhua	winter	P	landrace
60	**H-172**	ZM003145	China	府麦	Fu Wheat	Semi winter	I	landrace
61	**H-180**	ZM011525	China	大春白四棱麦 (2)	Dachunbai 4-rowed Wheat	Semi winter	I	landrace
62	**H-185**	ZM018930	China	边巴春麦-6	Bianba Spring Wheat-6	Spring	I	commercial
63	**H-189**	ZM008347	China	康定小麦	Kangding Wheat	Semi winter	I	landrace
64	**H-195**	ZM012760	China	大白麦	Dabai Wheat	Semi winter	I	landrace
65	**H-197**	ZM012793	China	火里炎	Huoliyan	Semi winter	E	landrace
66	**H-201**	ZM004780	China	金黄麦	Jinhuang Wheat	Semi winter	E	landrace
67	**H-204**	ZM012810	China	白齐头	Baiqitou	Semi winter	I	landrace
68	**H-207**	ZM009803	China	甘麦8号	Ganmai N 8	Semi winter	E	commercial
69	**H-211**	ZM017354	China	互助红	Huzhuhong	Semi winter	I	Landrace
70	**H-214**	ZM017313	China	会宁10号	Huining N 10	Semi winter	E	commercial

No	Genotype	Germplasm number	Origin	local name	English name	Growth habit	Growth type	category
71	**H-220**	ZM023315	China	兴义4号	Xingyi Number 4	Semi winter	E	commercial
72	**H-221**	ZM010564	China	凤麦11	Feng Wheat	Semi winter	E	commercial
73	**H-222**	ZM007916	China	同家坝小麦	Tongjiabei Wheat	winter	I	landrace
74	**H-223**	ZM007925	China	红花麦	Honghua Wheat	Semi winter	I	landrace
75	**H-224**	ZM008547	China	白麦子	Baimaizi	Semi winter	I	landrace
76	**H-225**	ZM008365	China	成都光头	Chengduguangtou	Semi winter	E	landrace
77	**H-227**	ZM008598	China	白花麦	Baihua Wheat	Semi winter	E	landrace
78	**H-228**	ZM008249	China	换香果	Huangxiangguo	winter	E	landrace
79	**H-229**	ZM004029	China	汉中白	Hanzhongbai	winter	I	landrace
80	**H-232**	ZM012545	China	红须麦	Hongxu Wheat	Semi winter	I	landrace
81	**H-233**	ZM011741	China	紫皮	Zipi	Semi winter	I	landrace
82	**H-235**	ZM020144	China	红芒子	Hongmangzi	Semi winter	E	landrace
83	**H-236**	ZM008636	China	鱼鳅麦	Yuqiu Wheat	Semi winter	E	landrace
84	**H-237**	ZM011644	China	阳麦	Yangmai	winter	E	landrace
85	**H-239**	ZM008809	China	猪屎麦	Zhushi Wheat	winter	E	landrace
86	**H-240**	ZM012032	China	扁头光壳麦	Biantouguangke Wheat	Semi winter	E	landrace
87	**H-241**	ZM011859	China	长芒石扁头	Changmangshibiantou	Semi winter	E	landrace
88	**H-242**	ZM012061	China	猪狗麦	Zhugou Wheat	winter	I	landrace
89	**H-247**	ZM005188	China	红冬麦	Hongdong Wheat	winter	E	landrace
90	**Hyperion**		United Kingdom			winter	P	landrace

91	**KARAGAN**	winter	I	landrace

No	Genotype	Germplasm number	Origin	local name	English name	Growth habit	Growth type	category
92	**Mackellar**	Australia			winter	E	landrace	
93	**Revenue**		Australia		winter	E	landrace	
94	**SEAGULL**					winter	P	landrace
95	**SURHAK MESTNYJ**					winter	E	landrace
96	**SW95 50292**					winter	E	landrace
97	**Wheat-2HBYDV**		China			winter	I	landrace
98	**WL-wheat**		China			winter	I	landrace
99	**Yannong 15**		China			winter	E	commercial

Note: I = Intermediate, P = Prostrate and E = Erect.

Annex.2(a). Days to GS01, days to GS21, days to forage cut (GS31) and days to GS45 taken in field trial by 99 wheaat genotypes for cut treatment and control at Mount Pleasant Laboratories, Tasmania, during the growing season 10 March to 30 September 2016.

	Days from sowing				
Variety	**GS01**	**GS21**	**GS31**	**GS45**	
				Control	**Cut**
073/44	7.7	65	113.6	158	170
CS170	6.3	26	131	165	168.67
FERRUGINEUM	7.7	26.33	68	126	159
H-019	7.7	35	126	163	170
H-020	6.3	26.66	132	164	169
H-021	7.7	26	68	128	161
H-022	8.3	28.33	109.6	126	134
H-024	7.0	26	126	159	170
H-028	7.0	26	83	159	170
H-037	7.0	26	126	161	170
H-038	7.0	25.33	122.6	163	170
H-039	7.0	27.66	126	148	168
H-044	7.7	28	131	144	168
H-045	7.7	26.33	68	151	161
H-046	7.7	27	68	130	162
H-048	7.7	27	68	128	158
H-049	7.7	27	83	132	163
H-051	7.7	28	83	132	163
H-053	7.7	29	83	137	162
H-054	7.7	28.33	97	141.33	159
H-057	7.7	26	97	142	159
H-058	8.3	29.33	97	161	159
H-059	8.3	26.33	124	128	159
H-060	7.7	28.33	131	141	163
H-061	8.3	28.33	113	113	159
H-064	8.3	29	113	126	158
H-068	8.3	30.66	53	129	144
H-069	7.7	29	131	141	163

	Days from sowing				
Variety	**GS01**	**GS21**	**GS31**	**GS45**	
				Control	**Cut**
H-074	7.7	27.33	53	145	161
H-076	8.3	27.33	57	131	160
H-093	8.3	26	89	153	148
H-116	7.7	26	126	158	170.67
H-117	7.7	26	97	138.33	163
H-118	7.7	28.66	133	148	170
H-119	7.7	27.33	131	159	169
H-120	7.7	26	83	158	168
H-121	7.7	29	126	161	170
H-126	7.7	31.66	97	129	131
H-129	7.7	32	126	163	168
H-137	7.7	28.66	53	103	144
H-138	8.3	30.66	113	141	159
H-141	7.7	29.66	68	155	159
H-143	7.7	30.33	83	165	172
H-144	8.7	28	136	157	170
H-145	6.3	27.33	133	158	170
H-147	7.7	28	126	168	170
H-148	7.7	28.66	131	163	170
H-149	7.7	31	122.3	164.33	171.67
H-153	7.7	25.33	123	163	170
H-154	7.7	26	95	166	171
H-159	7.7	27.66	124	169	170
H-160	7.7	27	123	162	171
H-164	7.7	27.33	126.3	141	173
H-165	8.3	30.33	124	137	155
H-167	7.7	26.33	122	131.33	167
H-168	7.7	28.33	100.6	140	168
H-169	7.7	28.66	124.6	183	169
H-170	7.7	28.33	53	163	173

	Days from sowing				
Variety	GS01	GS21	GS31	GS45	
				Control	Cut
H-171	7.7	30	119	128	168
H-172	7.7	29	57	133	173
H-180	7.7	27	53	153	170
H-185	7.7	26	95	137	158
H-189	7.7	26	52	136	145
H-195	7.7	28	82	131	273
H-197	8.3	31	53	148	175
H-201	8.3	27	53	126	159
H-204	7.7	26	53	158	168
H-207	8.3	28	53	111	134
H-211	7.7	29	53	137	163
H-214	8.3	26	108	126	160
H-220	8.3	28	53	116	132
H-221	8.3	28	53	128	172
H-222	7.7	28	95	132	158
H-223	7.7	29	53	126	158
H-224	7.7	27	53	141	163
H-225	8.3	30	113	128	156
H-227	8.3	28	53	134	145
H-228	8.3	28	53	124	159
H-229	7.7	28	53	150	158
H-232	7.7	25	126	141	158
H-233	7.7	26	53	145	158
H-235	8.3	30	53	127	168
H-236	8.3	28	113	132	166
H-237	8.3	29	53	159	163
H-239	8.3	28	122	159	173
H-240	8.3	28	57	141	159
H-241	8.3	31	57	144	160

	Days from sowing				
Variety	**GS01**	**GS21**	**GS31**	**GS45**	
				Control	**Cut**
H-242	7.7	28	131	145	162
H-247	8.3	28.66	53	103	159
Hyperion	7.7	26.66	131	163	170
KARAGAN	7.7	26.66	68	126	168
Mackellar	8.3	26.33	53	134	138
Revenue	8.3	30.33	53	161	170
SEAGULL	7.7	25.33	131	162	170
SURHAK-MESTNYJ	8.3	28	53	141	164
SW95-50292	8.3	27.33	53	126	163
Wheat-2HBYDV	8.3	29.66	117	144	163
WL-wheat	8.3	28.33	53	128	145
Yannong-15	8.3	28	53	134	166
LSD Value	0.7	2.8	5.4	8.5	15.4

Annex 2 (b). Plant height (cm), No of tillers and leaves at GS31 and GS45 observed in field trial of 99 wheat genotypes (including one cut and control treatment for GS45) at Mount Pleasant Laboratories, Tasmania, during the growing season 10 March to 30 September 2016.

	Plant height			**Number / plant (GS31)**	
Variety	**GS31**	**GS45**		**Tillers**	**Leaves**
		Control	**Cut**		
073/44	33.33	37	42	8.33	5
CS170	21.33	22	25	15.33	5
FERRUGINEUM	25.33	48	60	4	4
H-019	24	19	25	6.33	4.33
H-020	20.33	25	28	14.66	5
H-021	29.33	43	50	5.66	4
H-022	34.33	55	62	8	4.66
H-024	30.66	40	48	9.33	4.66
H-028	20	28	36	7	4
H-037	29.66	33	38	5.66	4.33
H-038	23.66	35	49	10.33	4.66
H-039	20	33	36	11	5
H-044	22	19	30	12.33	4.66
H-045	38	48	54	7.33	4.33
H-046	37.66	44	65	5.66	4
H-048	24.33	40	66	5	4
H-049	28.66	30	55	7.66	5
H-051	46.66	38	52	8	4.66
H-053	40.66	33	50	9.66	4.33
H-054	34	36	47	8	4
H-057	32	33	49	9	4
H-058	30.33	39	43	8.33	5
H-059	30	55	48	7	5
H-060	40	50	67	9	5
H-061	33.66	60	40	7.33	4.33
H-064	37.33	56	59	11.33	4.33
H-068	25	55	60	4	3
H-069	37	51	67	9	5

	Plant height			Number / plant (GS31)	
Variety	**GS31**	**GS45**		**Tillers**	**leaf**
		Control	**Cut**		
H-074	20.66	41	51	5.66	3.66
H-076	36	50	52	7	4
H-093	37	45	60	8	5
H-116	25.66	40	42	10.33	4.33
H-117	32.33	35	49	8.33	4
H-118	22.66	22	28	11.66	4.66
H-119	31	38	42	9	5
H-120	13.33	32	40	6.66	4.33
H-121	23.66	43	40	8.66	4.33
H-126	25	35	50	8	5
H-129	28.66	43	46	11.66	5
H-137	29.33	48	50	5	4
H-138	31.33	42	43	8.66	5
H-141	26	50	60	8.66	5
H-143	19.5	40	44	7	5
H-144	22.33	25	32	10	5
H-145	22	24	31	15	5
H-147	24	35	45	10	5
H-148	21.66	30	35	11.33	5
H-149	28	50	55	10	5
H-153	25.66	35	49	11.33	4.66
H-154	38	40	52	9.66	4.66
H-159	34.66	45	54	13	5
H-160	28.66	42	55	12	5
H-164	34.66	50	54	11.66	5
H-165	31	60	60	9.66	5
H-167	32.33	56	56	10.33	4.66
H-168	36.33	48	60	8.66	5
H-169	33.66	47	55	6.66	5
H-170	28.66	43	56	6.66	4.66

Variety	Plant height			Number / plant (GS31)	
	GS31	GS45		Tillers	leaf
		Control	Cut		
H-171	30	28	35	8.33	5
H-172	35.66	56	55	10	5.33
H-180	25	29	38	6	4
H-185	24	49	60	11.66	4
H-189	30	45	55	6.66	4
H-195	37.33	45	62	9.66	4.33
H-197	33.33	45	55	4.33	3.33
H-201	29.33	52	71	5	3
H-204	28.33	30	55	5.66	4
H-207	32.16	58	63	4	3
H-211	26.66	51	70	5	3
H-214	29.33	51	60	8.33	4
H-220	30.66	56	60	5	3
H-221	30.66	50	65	5	3
H-222	41.66	40	68	8	5
H-223	25	51	60	6	4
H-224	22.66	56	63	5	4
H-225	42.33	47	60	8.66	4.66
H-227	25.66	50	54	4	3
H-228	29	50	59	5	4
H-229	29.66	47	62	6	4
H-232	40	59	57	10	4
H-233	26.33	48	70	5.33	4
H-235	25.33	35	59	5	4
H-236	32.33	57	60	9.66	4
H-237	25.66	43	52	7	3.33
H-239	31.66	50	53	7.33	4.33
H-240	45	35	48	6.33	4.33
H-241	45.66	35	43	8.66	4

Variety	Plant height			Number / plant (GS31)	
	GS31	GS45		Tillers	leaf
		Control	Cut		
H-242	35.5	42	58	9	5
H-247	32	55	50.3	6	4
Hyperion	19	25	35	8	5
KARAGAN	26	38	60	5	4
Mackellar	20	64	65	6	3
Revenue	25.33	22	28	4	3
SEAGULL	20.66	19	25	10	5
SURHAK-MESTNYJ	18.66	50	70	5	4
SW95-50292	28.66	47	52	8	5
Wheat-2HBYDV	25.33	55	60	7	3
WL-wheat	22.66	48	66	4	4
Yannong-15	35.5	42	58	9	5
LSD	4.8	0.04	4.7	1.5	0.4

Annex 2 (c). Forage yield (DM t ha^{-1}) obtained by cutting at 5 cm above ground level at GS31 and total biomass yield (t ha^{-1}) by cutting at ground level at GS31 by 99 genotypes grawn in a field trial at Mount Pleasant Laboratories, Tasmania, during the growing season 10 March to 30 September 2016.

Variety	Forage yield (t ha^{-1})	Total biomass yield (t ha^{-1})
073/44	0.77	1.56
CS170	1.09	2.48
FERRUGINEUM	0.85	1.84
H-019	0.5	0.9
H-020	0.68	1.82
H-021	0.89	1.76
H-022	0.73	1.42
H-024	1.76	3.15
H-028	0.79	1.82
H-037	0.74	1.78
H-038	1.1	1.94
H-039	0.69	1.36
H-044	0.72	1.44
H-045	1.22	2.18
H-046	0.79	1.66
H-048	0.76	1.65
H-049	1.32	2.44
H-051	2.23	3.39
H-053	1.78	2.83
H-054	1.38	2.23
H-057	1.35	2.19
H-058	0.66	1.3
H-059	0.69	1.36
H-060	0.72	1.38
H-061	0.74	1.46
H-064	0.85	1.61
H-068	0.75	1.55
H-069	0.93	1.73
H-074	0.68	1.51

Variety	Forage yield (t ha^{-1})	Total biomass yield (t ha^{-1})
H-076	1.43	2.19
H-093	1.26	2.06
H-116	0.97	2.52
H-117	1.38	2.23
H-118	0.77	1.48
H-119	0.7	1.41
H-120	1.19	2.37
H-121	0.69	1.54
H-126	0.57	1.24
H-129	0.74	1.44
H-137	0.52	1.31
H-138	0.54	1.21
H-141	1.13	2.32
H-143	0.51	1.26
H-144	0.66	1.28
H-145	0.83	1.9
H-147	0.92	1.59
H-148	0.64	1.62
H-149	0.99	1.79
H-153	1.16	1.96
H-154	1.31	2.26
H-159	1.01	1.81
H-160	1.09	1.9
H-164	0.68	1.46
H-165	0.57	1.34
H-167	0.8	1.59
H-168	0.7	1.44
H-169	0.52	1.17
H-170	0.8	1.71
H-171	0.88	1.64

Variety	Forage yield (t ha^{-1})	Total biomass yield (t ha^{-1})
H-172	1	2.05
H-180	0.97	1.81
H-185	0.79	1.72
H-189	0.84	1.73
H-195	1.06	2.48
H-197	0.91	1.78
H-201	0.83	1.63
H-204	0.98	1.79
H-207	1.11	1.94
H-211	0.84	1.64
H-214	0.83	1.58
H-220	1.09	1.85
H-221	0.89	1.75
H-222	1.4	2.16
H-223	0.97	1.8
H-224	0.74	1.41
H-225	0.65	1.38
H-227	0.87	1.64
H-228	0.83	1.66
H-229	1.07	1.86
H-232	1.9	2.9
H-233	0.87	1.65
H-235	0.93	1.85
H-236	1.05	1.9
H-237	0.84	1.66
H-239	1.16	1.91
H-240	1.57	2.55
H-241	1.50	2.42

Variety	Forage yield (t ha^{-1})	Total biomass yield (t ha^{-1})
H-242	0.96	1.63
H-247	0.72	1.52
Hyperion	0.6	1.26
KARAGAN	0.62	1.44
Mackellar	0.63	1.39
Revenue	0.64	1.41
SEAGULL	1.08	1.81
SURHAK MESTNYJ	0.99	1.91
SW95 50292	0.81	1.74
Wheat-2HBYDV	0.84	1.68
WL-wheat	0.66	1.45
Yannong 15	0.76	1.64
LSD	0.19	0.59

Annex 2 (d). Growing degree days (°Cd) to GS01, GS21, GS31 and GS45 accumulated in field trial by 99 genotypes of wheat for cut and control treatment at Mount Pleasant Laboratories, Tasmania, during the growing season March to September 2016.

	Growing degree days (°Cd)				
Genotype	**GS01**	**GS21**	**GS31**	**GS45**	
				Control	**Cut**
073/44	146.6	397	1301.5	1635.4	1727.7
CS170	126.3	396	1446.2	1697	1707.8
FERRUGINEUM	146.6	397	931.8	1400.7	1645.6
H-019	146.6	511	1400.7	1683.35	1727.7
H-020	126.3	404	1453.6	1690.7	1719
H-021	146.6	396	931.8	1419.05	1665.2
H-022	155.9	396	1270.3	1400.7	1468.3
H-024	136.5	393	1400.7	1645.6	1727.7
H-028	135.9	394	1044.5	1645.6	1727.7
H-037	136.5	385	1400.7	1665.25	1727.7
H-038	136.5	417	1374.6	1683.35	1727.7
H-039	136.5	420	1400.7	1559.55	1713.2
H-044	146.6	401	1446.2	1533.55	1713.2
H-045	146.6	408	931.8	1578.05	1665.2
H-046	146.6	408	931.8	1435.85	1676.3
H-048	146.6	406	931.81	1419.05	1635.4
H-049	146.6	413	1044.5	1453.9	1683.3
H-051	146.6	434	1044.5	1453.9	1683.3
H-053	146.6	426	1044.5	1483.3	1676.3
H-054	146.6	396	1171.6	1514.7	1601.9
H-057	146.6	437	1171.6	1518.55	1645.6
H-058	155.9	401	1166.5	1665.25	1645.6
H-059	155.9	426	1387.6	1419.05	1645.6
H-060	151.3	425	1446.2	1514.7	1683.3
H-061	155.9	455	1293.1	1293.1	1645.6
H-064	155.9	435	1293.1	1400.7	1635.4
H-068	155.9	413	752.4	1426.45	1533.5
H-069	151.3	397	1446.2	1514.7	1683.3
H-074	151.3	396	752.4	1539.9	1544.9

Genotype	GS01	GS21	GS31	GS45	
				Control	Cut
H-076	155.9	412	799.5	1446.2	1653.8
H-093	155.9	396	1103.2	1594.7	1559.5
H-116	146.6	396	1400.7	1635.4	1725.2
H-117	146.6	430	1171.6	1493.7	1618.4
H-118	146.6	411	1458.6	1559.5	1727.7
H-119	146.6	396	1446.2	1645.6	1719
H-120	146.6	434	1044.5	1635.4	1713.2
H-121	146.6	469	1400.7	1665.2	1727.7
H-126	146.6	474	1171.6	1426.4	1446.2
H-129	146.6	428	1400.7	1683.3	1713.2
H-137	146.6	455	752.4	1221.8	1533.5
H-138	155.9	442	1293.1	1514.7	1645.6
H-141	146.6	450	931.8	1609.3	1645.6
H-143	146.6	420	1044.5	1697	1740.8
H-144	163.3	413	1478.3	1624.4	1727.7
H-145	126.3	420	1458.6	1635.4	1727.7
H-147	146.6	430	1400.7	1713.2	1727.7
H-148	146.6	461	1446.2	1683.3	1727.7
H-149	146.6	385	1372.8	1692.4	1738.5
H-153	146.6	396	1379.2	1683.3	1727.7
H-154	146.6	417	1154.9	1701.9	1734.7
H-159	146.6	413	1385.7	**1719**	1727.7
H-160	146.6	412	1378.2	1676.3	1734.7
H-164	146.6	453	1404.1	1514.7	1746.8
H-165	155.9	398	1385.1	1483.3	1609.3
H-167	146.6	426	1369.5	1440.1	1633.6
H-168	146.6	429	1198	1504.8	1713.2
H-169	146.6	425	1390.2	1698.6	1739.5
H-170	146.6	457	752.4	1683.3a-c	1746.8
H-171	146.6	412	1345.8	1419p-r	1713.2

Growing degree days (°Cd) applies to columns GS01–GS45.

Genotype	Growing degree days (^oCd)				
	GS01	GS21	GS31	GS45	
				Control	Cut
H-172	146.6	443	799.5	1460	1746.8
H-180	146.6	413	752.4	1594	1727
H-185	146.6	401	1154.9	1483.3	1635.4
H-189	146.6	396	744.5	1477.1	1544.1
H-195	146.6	426	1036.4	1446.2	1906.4
H-197	155.9	460	752.4	1559.5	1767.7
H-201	155.9	408	752.4	1400.7	1645.6
H-204	146.6	403	752.4	1635.4	1713.2
H-207	155.9	425	752.4	1276.9	1468.3
H-211	146.6	441	752.4	1483.3	1683.3
H-214	155.9	401	1251.1	1400.7	1656.5
H-220	155.9	425	752.4	1327.1	1412.6
H-221	155.9	421	752.4	1400.0	1740.8
H-222	146.6	425	1154.9	1453.9	1635.4
H-223	146.6	425	752.4	1400.7	1635.4
H-224	146.6	436	752.4	1514.7	1683.3
H-225	155.9	417	1293.1	1419	1617.5
H-227	155.9	453	752.4	1468.3	1539.9
H-228	155.9	421	752.4	1388.2	1543.2
H-229	146.6	421	752.4	1585.7	1616.2
H-232	146.6	426	1400.7	1514.7	1635.4
H-233	151.3	387	752.4	1539.9	1635.4
H-235	155.9	396	752.4	1411	1713.2
H-236	155.9	453	1293.1	1453.9	1701.9
H-237	155.9	428	752.4	1645.6	1683.3
H-239	155.9	442	1369.2	1645.6	1746.8
H-240	155.9	421	799.5	1514.7	1645.6
H-241	155.9	421	799.5	1533.5	1656.5

Genotype	Growing degree days (ºCd) GS01	GS21	GS31	GS45 Control	GS45 Cut
H-242	151.3	422	1446.2	1539.9	1676.3
H-247	155.9	428	752.4	1221.8	1645.6
Hyperion	146.6	433	1446.2	1683.3	1727.7
KARAGAN	146.6	394	931.9	1400.7	1713
Mackellar	155.9	405	752.4	1468.3	1488.7
Revenue	155.9	404	752.4	1665.2	1727.7
SEAGULL	146.6	401	1446.2	1676.3	1727.7
SURHAK-MESTNYJ	155.9	453	752.4	1514.7	1690.3
SW95-50292	155.9	385	752.4	1400.7	1683.3
Wheat-2HBYDV	155.9	417	1331.2	1533.5	1683.3
WL-wheat	155.9	413	752.4	1419	1539.9
Yannong-15	151.3	442	752.4	1468.3	1701.9
LSD	10.3	33.7	40.67	59.3	109.3

Annex .3. Anova tables for Chapter 3. DF = degrees of freedom, MS = mean squares.

Plant height of 4 genotypes as affected by 4 cutting treatments at GS25

	DF	MS	F value	Pr > F
varieties	3	40	2.99	0.0423
cuts	4	40	1.27	0.2983
varieties*cuts	12	40	0.76	0.68

Plant height of 4 genotypes as affected by 4 cut treatments after 14 days of cutting

	DF	MS	F value	Pr>F
varieties	3	40	11.9	<.0001
cuts	4	40	53.78	<.0001
varieties*cuts	12	40	1.96	0.055

Plant height of 4 genotypes as affected by 4 cut treatments at GS31

	DF	MS	F value	Pr>F
varieties	3	40	46.13	<.0001
cuts	4	40	25.73	<.0001
varieties*cuts	12	40	2.45	0.017

Forage dry matter plant $^{-1}$ of 4 genotypes as affected by 4 cut treatments at GS25

	DF	MS	F value	Pr>F
varieties	3	40	1.62	0.1996
cuts	4	40	115.68	<.0001
varieties*cuts	12	40	1.8	0.0819

Total biomass plant^{-1} of 4 genotypes as affected by 4 cut treatments at GS31

	DF	MS	F Value	Pr>F
varieties	3	40	2.6	0.0655
cuts	4	40	25.31	<.0001
varieties*cuts	12	40	1.4	0.2047

Chlorophyll content of 4 genotypes as affected by 4 cut treatments at GS25

	DF	MS	F Value	Pr>F
varieties	3	40	1.89	0.1469
cuts	4	40	13.49	<.0001
varieties*cuts	12	40	0.7	0.7389

Chlorophyll content of 4 genotypes as affected by 4 cut treatments at GS31

	DF	MS	F Value	Pr>F
varieties	3	40	13.82	<.0001
cuts	4	40	15.92	<.0001
varieties*cuts	12	40	2.46	0.0163

Annex 4 Anova tables for Chapter 4. DF = degrees of freedom, MS = mean squares.

Plant height of 3 genotypes as affected by 5cut treatments at GS25

	DF	MS	F Value	Pr>F
Replication	2	4	0.97	0.4534
Genotypes	2	4	15.82	0.0126
cuts	5	30	1.08	0.3916
Genotypes*cuts	10	30	0.91	0.5391

Plant height of 3 genotypes as affected by 5 cutting treatments at GS31

	DF	MS	F Value	Pr>F
Replication	2	6.37	2.06	0.2038
Genotypes	2	4	97.81	0.0004
cuts	5	10	22.73	<.0001
Genotypes*cuts	10	20	13.42	<.0001

Forage yield plant^{-1} of 3 genotypes as affected by 5 cut treatments at GS25

	DF	MS	F Value	Pr>F
Replication	2	5.29	1.32	0.342
Genotypes	2	4	49.42	0.0015
cuts	5	10	71.73	<.0001
Genotypes*cuts	10	20	7.38	<.0001

Biomass yield plant^{-1} of 3 genotypes as affected by 5 cut treatments at GS31

	DF	MS	F Value	Pr>F
Replication	2	34	0.57	0.5735
Genotypes	2	34	0.76	0.4738
cuts	5	34	46.38	<.0001
Genotypes*cuts	10	34	1.15	0.3557

Chlorophyll content of 3 genotypes as affected by 5 cut treatments at GS25

	DF	MS	F Value	Pr>F
Replication	2	5.09	0.23	0.8037
Genotypes	2	4	1.53	0.3208
cuts	5	10	0.7	0.639
Genotypes*cuts	10	20	1.4	0.2489

Chlorophyll content of 3 genotypes as affected by 5 cut treatments at GS31

	DF	MS	F Value	Pr>F
Replication	2	4.82	1.27	0.3603
Genotypes	2	4	8.71	0.0349
cuts	5	10	16.04	0.0002
Genotypes*cuts	10	20	3.91	0.0046

Annex 5. Anova tables of parameters evaluated in Chapter 5. DF = degrees of freedom, MS = mean squares.

Calendar days taken to reach GS01 by 99 genotypes

	DF	MS	F value	Pr>F
Replications	2	394	569.37	<.0001
Treatment	1	394	0.5	0.4786
Genotypes	98	394	3.18	<.0001
Treatment*genotypes	98	394	0.08	1

Calendar days taken to reach GS21 by 99 genotypes

	DF	MS	F value	Pr>F
Replications	2	1	0.89	0.5987
Treatment	1	2	0	0.9681
Genotypes	98	392	1.17	0.1502
Treatment*genotypes	98	392	0.79	0.917

Calendar days taken to reach GS31 by 99 genotypes

	DF	MS	F value	Pr>F
Replications	2	394	1.71	0.1822
Treatment	1	394	0	1
Genotypes	98	394	261.34	<.0001
Treatment*genotypes	98	394	0	1

Calendar days taken to reach GS45 by 99 genotypes as affected by cut and control treatments.

	DF	MS	F value	Pr>F
Replications	2	1	0.03	0.9684
Treatment	1	2	605.31	0.0016
Genotypes	98	392	19.78	<.0001
Treatment*genotypes	98	392	12.35	<.0001

Plant height of 99 genotypes at GS31

	DF	MS	F value	Pr>F
Replications	2	394	7.03	0.001
Treatment	1	394	0	1
Genotypes	98	394	14.28	<.0001
Treatment*genotypes	98	394	0	1

Number of Tiller plant^{-1} of 99 genotypes at GS31.

	DF	MS	F value	Pr>F
Replications	2	394	7.7	0.0005
Treatment	1	394	0	1
Genotypes	98	394	22.35	<.0001
Treatment*genotypes	98	394	0	1

Number of leaf mains stem^{-1} of 99 genotypes at GS31

	DF	MS	F value	Pr>F
Replications	2	394	3.61	0.028
Treatment	1	394	0	1
Genotypes	98	394	17.71	<.0001
Treatment*genotypes	98	394	0	1

Plant height of 99 genotypes at GS45

	DF	MS	F value	Pr>F
Replications	2	392	1	0.3688
Treatment	1	392	7246864	<.0001
Genotypes	98	392	388221	<.0001
Treatment*genotypes	98	392	51426.8	<.0001

Growing degree days accumulated by 99 genotypes at GS01

	DF	MS	F value	Pr>F
Replications	2	394	551.59	<.0001
Treatment	1	394	0.47	0.4939
Genotypes	98	394	3.3	<.0001
Treatment*genotypes	98	394	0.08	1

Growing degree days accumulated by 99 genotypes at GS21

	DF	MS	F value	Pr>F
Replications	2	1	0.8	0.6194
Treatment	1	2	0.01	0.9182
Genotypes	98	392	1.3	0.0412
Treatment*genotypes	98	392	0.7	0.9818

Growing degree days accumulated by 99 genotypes at GS31

	DF	MS	F value	Pr>F
Replications	2	394	1.46	0.2326
Treatment	1	394	0	1
Genotypes	98	394	293.55	<.0001
Treatment*genotypes	98	394	0	1

Growing degree days accumulated by 99 genotypes as affected by cut and control treatment at GS45

	DF	MS	F value	Pr>F
Replications	2	1	0.78	0.6248
Treatment	1	2	1064.08	0.0009
Genotypes	98	392	22.8	<.0001
Treatment*genotypes	98	392	13.07	<.0001